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TRANSLATION

INDENTIFICATION AND INVESTIGATION OF HEAT-RESISTANT ALLOYS ON A Fe - Ni -Cr BASE

By

M. V. Pridantsev, E. I. Belikova, et. al.

FOREIGN TECHNOLOGY DIVISION

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IDENTIFICATION AND INVESTIGATION OF HEAT-RESISTANT ALLOYS ON A Fe – Ni – Cr BASE

M.V. Pridantsev, E.I. Belikova and Ye.G. Nazarov

1. Selection of Alloy Base

The present paper considers the results of work toward identification of cheaper heat-resistant alloys that possess adequately high hot strength at temperatures up to 750° together with satisfactory mechanical and technological properties – such as might be used as substitutes for similar alloys based on nickel as a material for the disks, wheels and blades of gas-turbine engines operating at 550–750°. In the study, a time to failure of no less than 100 hours at 750° and a stress of 30 kg/mm^2 was taken as the criterion for evaluating hot strength.

Analysis of the properties of alloys known from the literature and in use abroad and in the USSR indicates that many alloys have long-term strength either inferior to the parameter indicated or equal or approximately equal to it (Table 1). Thus, alloys containing nickel and cobalt and alloyed with molybdenum or tungsten (Timkenalloy, S-495, LCN-155, Diskalloy, EI395, EI434) have ultimate strengths from 15 to 20 kg/mm^2 after 100 hours at 750°. The widely used type EI437B nickel-based alloy has an ultimate long-term strength (100 hours) of 30 kg/mm^2, and only more heavily alloyed nickel and nickel-cobalt types possess higher hot strengths.

In a search for more economical heat-resistant alloys, we smelted out various alloys on the following bases: 15/20, 15/25, 15/30, 15/35, 15/40, 15/50, 15/60 (chromium and nickel contents, respectively).

Preliminary investigation of the alloys indicated that the alloys on the 15/35 and 15/25 bases can guarantee the required hot-strength properties (Table 2). Here, the alloy with 35% Ni has higher heat-resistant properties than the alloys with 20 and 25% Ni.

The 15% Cr content in the type EI787 alloy is necessary to insure that the alloy will be heat-resistant and high-temperature corrosion-resistant.

TABLE 1

1 Сплав	2 Основной химический состав, %										3 Температура испытания, °C	4 Предел длительной прочности за 100 час., кг/мм²
	C	Cr	Ni	Co	Mo	W	Ti	Al	Nb	B		
5 США												
6 Тимкеналлой (1,2)	0,10	16	25	—	6	—	—	—	—	0,13	650 732	40 19,7
19—9 DL [1]	0,30	20	9	—	1,2	1,2	—	—	0,3	—	650 760	42 19,5
S-495 [1]	0,50	14	20	—	4	3,5	—	—	4,5	—	650	24,6
LCN-155 [1]	0,40	21	21	20	3	2	—	—	1,0	—	650 732	40,5 25,3
7 Дискаллой [1,3]	0,04	13,5	25	—	4	—	2,0	—	—	—	734	32
S-816 [1]	0,4	20	20	43	4	4	—	—	4	—	650 730	42 25,2
A-286 [4]	—	15	26	—	1,25	0,3 V	2,0	1,0Mn	—	0,0017	750	21
W-545 [5]	0,03	13	26	—	3	—	2,8	0,1	—	0,015—0,030	650	53
8 Д-979	0,05	15	45	—	4	4	3	1	—	0,010	650	63
9 ИНК 0901	0,08	13	42	—	6	—	2,5	—	—	—	650 732	55 38
M-308	0,1	14	33	—	4	0,5	2,0	0,25	—	Zr 0,26	Нет данных 10	
11 Англия												
12 Нимоник-80 [1]	0,05	20	76	—	—	—	2,3	1,0	—	—	650 750	47 27,5
Нимоник-90 [1]	0,08	20	58	16	—	—	2,3	1,4	—	—	650 750	53,5 31,5
13 СССР												
ЭИ395	0,1	16	26	—	6	—	—	1,5Mn	—	—	750	15
ЭИ434	0,35	13	13	10	2	3	—	—	1,25	—	750	17
ЭИ481 Б	0,3 0,4	12,5	6,5	—	1,4	—	1,5V	7,0Mn	1,4	—	750	25
14 ЭИ437 Б	0,08	20	Осн.	—	—	—	2,5	1	—	0,010	750	30
ЭИ696	0,08	11	22	—	—	—	3	0,8	—	0,015	700 750	40 28
ЭИ787	0,08	15	35	—	—	3	3	1	—	0,015	750	30—34
ЭИ696 М	0,08	11	25	—	1,5	—	3	0,8	—	0,015	750	30

1) Alloy; 2) basic chemical composition, %; 3) test temperature, °C; 4) ultimate long-term strength (100 hours), kg/mm²; 5) USA; 6) Timkenalloy; [Key continued on page 3]

[Key to Table 1 continued]: 7) Diskalloy; 8) D-979; 9) INK 0901; 10) not available; 11) Great Britain; 12) Nimonic; 13) USSR; 14) EI437 B.

TABLE 2

1 Основа сплава (%) Cr–Ni	2 Содержание элементов %			3 Время до разрушения часы	δ, %	ψ, %	4 σ_b кг/мм² при 20°
	W	Al	Ti				
15–20	—	0,72	2,71	45	11,2	16,8	81,4
				52	8,8	16,8	79,4
				28,35	14,4	11,6	—
15–20	2,2	0,73	2,97	97	5,6	12,8	94,4
				85	8,0	7,6	95,4
				87,30	2,4	10,0	—
13–25	2,61	—	2,75	118,45	1,2	2,8	100,9
				141,35	4,4	0,8	102,9
				216,45	5 2,8	2,4	—
13–30	2,99	0,98	3,2[illegible]	3[illegible]3,10	Обрыв у галтели		109,0
				253,15	2,4	1,6	110,7
				303,45	1,2	2,0	—
15–35	3,0	1,03	2,90	313	6,0	3,2	114,4
				512	3,6	5,2	—
				4[illegible]7	6 1,2	0,8	-
				>[illegible]*	Снят не разрушенным		—
				3173*	2,8	3,6	—
15–35	3,61	0,91	3,09	455,25	1,2	3,2	—
				236	2,0	2,0	—
				601,40	1,6	2,0	—
				3212,30*	5,2	5,6	—
				3200,15*	2,0	1,6	—
15–35	1,93	0,85	3,01	316,45	5,6	10,4	112,9
				259,45	4,0	8,0	—
				295,40	4,8	7,1	—
				293	4,4	14,0	—

Note. 1. Heat-treatment conditions: 1200°, 2.5 hours, air + 750°, 16 hours, air. 2. 0.02–0.03% of B were introduced into the entire melt. 3. The long-term-strength tests were run at 750° and $\sigma = 30$ kg/mm² (for specimens marked by the asterisk, $\sigma = 20$ kg/mm²).

1) Alloy base (%), Cr–Ni; 2) content of elements, %; 3) time to failure, hours; 4) σ_b, kg/mm² at 20°; 5) broke at fillet; 6) removed unbroken.

A.M. Bordzyka [11] showed that chromium raises the creep resistance; here, the optimum content of this metal is 15–25%.

M.V. Pridantsev and G.V. Estulin [6] established that the introduction of 20% of Cr into the obsolescent nickel-titanium alloy raises its softening temperature by approximately 100°. This effect is accounted for by hardening of the solid solution by the chromium and inhibition of diffusion processes.

The influence of chromium was checked in the present study (with contents up to 20%).

The data obtained (Table 3) indicate that alloys with 15% Cr are not inferior as regards hot strength to alloys containing 20% Cr.

As follows from Table 3, alloys with 20% Cr have no advantages as regards hot-strength properties over alloys with 15% Cr.

TABLE 3

1 Номер плавки	2 Содержание элементов, %					4	5	δ, %	ψ, %
	Cr	W	Ti	Al	B (расч.) 3				
8693	15,18	3,00	2,90	0,94	0,03	750	313—512	3—6	3—5
402	15,05	2,80	3,15	1,07	0,03	800	323—402	4—7	4—11
403	15,23	2,00	3,07	0,88	0,02	800	223—330	4—10	8—9
3290	15,63	2,90	2,78	0,53	0,01	750	175—353	4—13	6—14
7937-1	20,5	2,50	2,92	0,72	0,01	800	140—343	4—5	5—6
7937-3	20,5	2,50	2,73	0,52	0,03	800	250—265	4—5	5—6

1) Melt No.; 2) content of elements, %; 3) B (calculated); 4) heat treatment: 1200°, 2.5 hours, air + aging for 16 hours at the following temperature, °C, in air; 5) time to failure, hours, at 750° and σ = 30 kg/mm^2.

The mechanical properties of alloys with 15 and 20% of Cr are practically identical. Consequently, the injection of 20% of Cr into alloys of the type under investigation is not advisable; 14-16% of Cr is quite sufficient to ensure adequate hot strength in the alloy (at working temperatures up to 800°).

Thereafter, we studied the influence of elements that alloy and harden the solid solution or form an intermetallic phase with nickel (W, Mo, Ti, Al, B and others); here, the optimum composition of the iron-nickel-chromium alloys and the optimum heat-treatment conditions should be selected.

All of the alloys investigated were dispersion-hardening due to the segregation of an $Ni_3(Ti, Al)$-type intermetallic phase.

Attempts to create alloys based on iron-nickel-chromium with 35% Ni that would be hardened only by aluminum (without titanium) proved unsuccessful.

2. Smelting and Forging Blanks from Experimental Melts

The alloys for study were smelted by fusing the charge materials together in 10-, 30- and 50-kg high-frequency furnaces with the basic crucible.

The crucible was first charged with FeCr (PB iron or Armco iron), Ni (000), W (metal) and Mo (metal), after partial fusion of which a slag of the following composition was introduced: 20% MgO, 65% CaO, 15% CaF_2 mixed with borkal'k (33% CaO + 67% Al powder). On fusion, the metal was deoxidized with an NiMg ligature (containing 15% Mg) in an amount based on 0.35% of Mg introduced into the melt, and then the slag was removed. Cryolite (Na_3AlF_6) was supplied to the surface of the molten metal, after which the Al was fed into the bath with the power to the furnace shut off, followed by FeTi at full furnace power. When the FeTi had melted, the AlBa ligature (50% Ba) was added and the cryolite was poured off. Cryolite assists in suppressing the combustion of Al and Ti; the melts formed in this manner were distinguished by stable contents of Ti and Al. Last of all, FeCe and FeB were injected into the metallic bath, and the metal was poured from the furnace after a holding time of 1-3 min.

The temperature of the metal prior to pouring was about 1500-1550° for all melts, and during decantation it was ~ 1410-1440°. The ingot deadheads were shrunk with iron thermite and the ingots were air-cooled. The charge materials were subjected to spectral analysis for their content of detrimental low-melting impurities (Pb, As, Sb, Sn, Bi and others), and only the purest of them were used for the melts.

Blanks 15-20 mm in diameter were made from the 7- to 17-kg ingots by flat-die forging. The heating temperature of the alloys during forging was 1100-1140°.

Alloys on the 15% Cr, 35% Ni base with $\leq$ 3% Ti, $\leq$ 1% Al and $\leq$ 4% W deform well without creating any difficulties in forging. Increasing the contents of the alloying and hardening elements makes deformation more difficult.

Tungsten makes deformation difficult; at contents of 10% in the ingots, fine cracks formed during forging. The heating temperature for alloys with 8-10% W must be raised to 1150°.

Molybdenum has approximately the same effect.

Niobium in the 15/35 alloy – even at a content of 1% – is noticeably detrimental to the forgeability of the ingots. Alloys of this type with 1.5% Nb deform satisfactorily.

The sharp drop in the forgeability of alloys containing niobium is accounted for by the influence of harmful low-melting impurities (Pb, Sn, Sb etc.), with which the niobium ligatures, ferroniobium and metallic niobium are usually contaminated.

Introduction of up to 1.5% of V into the 15/35 alloy has no essential influence on deformability. Aluminum raises the resistance to deformation. Increasing the aluminum content to 5-7% with 3% Ti and 3% W results in a sharp deterioration of forgeability; such ingots tear apart on forging. Raising the heating temperature does not improve the deformability of such alloys. With 0.010% B, the heating temperature may be raised to 1150-1160°; when the boron content is increased to 0.02-0.03% and above, this cannot be done, since the segregations of boride eutectic that appear along the boundaries and joints between the grains melt at this temperature.

On introduction of up to 0.02-0.03% B into the alloy, resistance to deformation increases markedly as compared to that of the boron-free alloys. Raising the boron content to 0.20% in the alloy having the basic composition results in a drop in technological plasticity. All of the laboratory-melt ingots were forged in the range from 1100 to 900°. The forged blanks (15-20 mm in diameter) were cooled in air.

3. Influence of Alloying Elements

An alloy of the following composition was investigated: 0.02-0.05% C; 0.1-0.4% Si; 0.08-0.2% Mn; 0.006-0.007% S; 0.004-0.01% P; 14-16% Cr; 35-36% Ni; 2-4% W; 2.8-3.1% Ti; 0.7-1.0% Al (remainder iron).

We studied the influence of secondary alloying elements introduced in the following quantities to reduce the iron content: 0-11% W; 0-10% Mo; 0-4% Ti; 0-5.6% Al; 0-0.2% B. Also studied was the influence exerted by niobium, vanadium, silicon, manganese and carbon.

In investigating the influence (exerted separately or jointly) by some of the elements, we studied the capacity of the alloys for hot deformation, their tendency toward dispersion hardening, and the influence exerted on the microstructure and mechanical and heat-resistance properties. The basic method for evaluating the heat resistance of the experimental alloys was the long-term strength test at 750° under a stress of 30 kg/mm^2 after hardening from 1200° (2.5 hours) in air and aging at 750° for 16 hours in air.

Influence of tungsten

Alloys based on 15% Cr, 35% Ni, 3% Ti and 1% Al with a variable tungsten content (2, 3.5, 5.5, 8.5 and 11%), remainder iron, were investigated. Table 4 presents the chemical compositions of some of the alloys studied. The high contents of titanium and aluminum in the alloys investigated made it possible to evaluate their properties as

TABLE 4

1 Номер плавки	2 Содержание элементов, %													
	C	Si	Mn	Cr	Ni	Fe	W	Al	Ti	3 B (расч.)	Ba (расч.)	Ce (расч.)	S	P
9513	0.05	0.18	0.08	15.98	35.28	4 Ост	—	0.90	2.91	0.03	0.2	0.02	0.007	0.006
9512	0.025	0.24	0.16	15.78	35.27	»	1.90	0.76	3.00	0.03	0.2	0.02	0.006	0.007
890	0.08	0.17	0.10	15.85	36.26	»	3.61	0.94	3.09	0.04	0.2	0.02	0.006	0.012
8602	0.02	0.03	Сл 6	15.01	36.17	»	5.61	1.05	2.97	0.03	0.2	0.02	0.004	0.007
10258	0.03	—	0.08	15.80	36.21	»	11.0	0.72	2.65	0.03	0.2	0.02	Не опр. 5	0.005

Note. The forgeability of all melts was satisfactory, except for melt 10258, in which fine cracks formed on forging.

1) Melt No.; 2) content of elements, %; 3) B (calculated); 4) rest; 5) not determined; 6) trace.

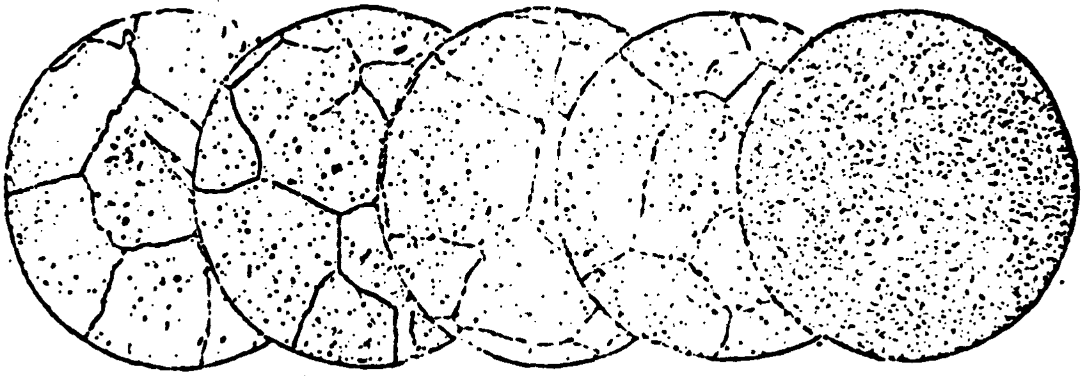

Fig. 1. Microstructure of type EI787 alloys with various tungsten contents. 100 x. Contents of tungsten (from left to right): 0, 2.8, 5.6, 8.7 and 11.0%. Treatment: 1180°, 2.5 hours, air.

functions of tungsten content.

According to microanalysis and hardness measurements, there is about 7-8% of dissolved tungsten in the Fe-Ni-Cr γ-solid solution of the alloy studied. After cooling from 1180° in air, the alloy with 8.7% W had a structure consisting of polyhedra of the γ-solid solution (grain-size rating 1-2) and a very small quantity of excess phase (Fig. 1). At 11% W, a large quantity of excess phase appears in the structure of the hardened alloy (grain-size rating 7-8). The hardness of the hardened alloys increases with increasing tungsten content.

Tungsten additives exert an essential influence on the dispersion-hardening processes of the alloy. With increasing tungsten content, the hardness of the alloys after aging increases (Fig. 2). With tungsten contents no smaller than 5.5%, the high hardness is retained after aging at 850° (> 300 HB) and even 900° (> 255 HB). The maximum on the dispersion-hardening curves corresponds to aging temperatures of 750-800°. Softening of all alloys containing 0-11% W begins at temperatures in excess of 800° (Fig. 2).

On dissolving in the Fe-Ni-Cr solid solution, the tungsten reduces the solubility of titanium and aluminum in it. In this case, a large quantity of hardened phase is segregated and, as a result, greater hardening of the alloy is attained.

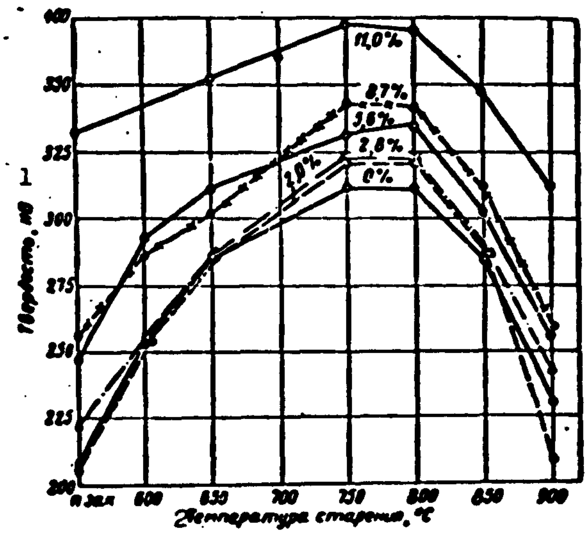

Fig. 2. Hardness of alloys with various tungsten contents as a function of aging temperature. Heat treatment: hardening from 1200°, 2.5 hours, air. 1) Hardness HB; 2) aging temperature, °C.

Moreover, dissolving in the Fe-Ni-Cr solid solution, tungsten — as in the alloys on the Ni-Cr base [6] — somewhat retards diffusion of titanium and aluminum and inhibits coagulation and solution of the in-

TABLE 5

W %	1 Время до разрушения		ψ, %	3 Механические свойства при 20°				
	2 часы	δ, %		4 σ_b кг/мм²	4 σ_s кг/мм²	δ, %	ψ, %	5 a_k кгм/см²
5	120	2,4	2,7	116,4	77,0	14,8	25,3	9,3
6	165	3,2	3,2	—	—	—	—	—

Note: 1. Heat treatment: 1150°, 8 hours, air + + 1050°, 4 hours, air + 750°, 16 hours, air.
2. The long-term strength tests were run at 750° and $\sigma = 30$ kg/mm².

1) Time to failure; 2) hours; 3) mechanical properties at 20°; 4) kg/mm²; 5) kg-m/cm².

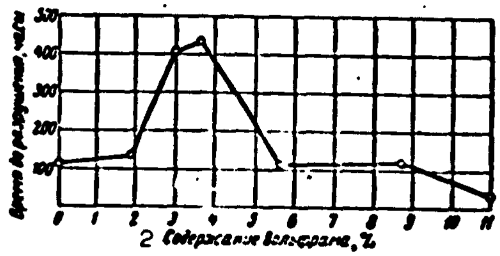

Fig. 3. Time to failure of EI787-type alloys with various tungsten contents: heat treatment: 1200°, 2.5 hours, air + + 750°, 16 hours, air. Tests at 750° and $\sigma = 30$ kg/mm². 1) Time to failure, hours; 2) tungsten content, %.

termetallic phase; as a result, softening of the alloy is retarded and its high-temperature strength is improved.

Tungsten raises the recrystallization temperature of Fe-Ni-Cr alloys.

After hardening from 1200° (2.5 hours) in air and aging for 16 hours at 750°, the longest time to failure (> 400 hours) at 750° and 30 kg/mm² was scored by an alloy with 3-4% W (Fig. 3). Under the same test conditions, alloys with 5-11% W fail considerably earlier (100-50 hours).

After hardening from a lower temperature (1150°, 8 hours, air) and aging (750°, 16 hours, air), the alloy with 6% W (Table 5) has the highest hot strength at 750°. Hardening from 1150° enables us to obtain a finer grain (rating 4-5) in the alloy with 6% W; together with the good heat-resistance at test temperatures from 750-800°, this ensures higher plastic and toughness properties.

Hardening of the alloy with introduction of higher tungsten contents (5-6%) makes it possible to raise heat resistance considerably for a test temperature of 800°. Thus, the time to failure of an alloy with 6% W (hardening from 1180°, 8 hours, air + aging at 800°, 16 hours, air) at 800° and $\sigma = 25$ kg/mm^2 is 150 hours. An alloy with 2% W fails after 20-30 hours under the same test conditions.

It was established in studies of laboratory and industrial melts that after heat treatment (hardening from 1170°, 4-8 hours, air + + 1050°, 4 hours, air + aging at 750-800°, 16 hours, air), an alloy with 2-4% W ensures satisfactory plastic and toughness properties in addition to excellent heat-resistance at 750° (Table 6).

This alloy satisfies a complex of specifications set forth for heat-resistant alloys to work under stress at temperatures up to 750°.

TABLE 6

1 Номер плавки	2 Содержание легирующих элементов, %			3 Время до разрушения, часы	4 Механические свойства при 20°				
	W	Ti	Al		5 σ_b кг/мм²	5 σ_s кг/мм²	δ, %	ψ, %	6 a_k кгм/см²
90766	2,72	3,03	1,24	200 200	124,6 128,8	90,2 92,3	14,0 17,6	15,4 16,0	5,0 5,2
91974	2,71	2,97	1,23	110 200	118,1 124,6	78,6 78,6	14,8 19,6	21,1 26,3	7,5 6,8
91992	2,78	2,98	0,88	110 200	126,1 123,6	84,0 84,6	16,0 14,8	19,1 19,1	4,9 4,8
92008	2,90	3,05	1,27	200 200	117,0 125,2	80,9 83,8	12,0 14,8	16,5 16,9	5,1 5,0
92537	2,73	2,84	1,09	110 200	116,1 122,1	80,6 81,4	12,4 14,2	17,5 19,1	4,3 5,3
77736	2,50	3,00	1,37	132 132	121,2 117,2	77,1 72,4	15,6 28,0	16,7 19,0	6,9 6,1
79175	2,47	3,07	1,09	247 247	116,2 115,0	67,5 67,5	19,6 19,6	20,6 20,6	6,0 6,6

Note. 1. Heat treatment of specimens of all melts: 1170°, 8 hours, air + 1050°, 4 hours, air + aging at 750°, 16 hours, air (except for melts 77736 and 79175: 1150°, 10 hours, air + + 1050°, 4 hours, air + aging at 830°, 16 hours, air). 2. Conditions of long-term-strength testing: 750°, $\sigma = 30$ kg/mm^2, all specimens removed without failure.

1) Melt No.; 2) content of alloying elements, %; 3) time to failure, hours; 4) mechanical properties at 20°; 5) kg/mm^2; 6) kg-m/cm^2.

A heat-treatment formula (hardening from 1150°, 8 hours, air + 1050°, 4 hours, air + aging 16 hours at 830°, air) that makes it possible to raise the plasticity of the material and ensure satisfactory heat-resistance properties (Table 6) has been worked out for special operating conditions of products made from heat-resistant alloys with 2-4% W.

A heat-resistant alloy of the following composition was selected on the basis of the results, for operation under stress at temperatures up to 750°: 15% Cr, 35% Ni, 2-4% W, 3% Ti, and 1% Al. The alloy with 5-6% W is useful for operation at 800°.

Influence of molybdenum

We investigated alloys with 15% Cr, 35% Ni, 3% Ti, 1% Al and variable molybdenum content, as follows: 1, 2, 3, 5, 6, 8 and 10%. The

TABLE 7

1 Номер плавки	2 Содержание элементов, %									4 Ковкость
	C	Si	Mn	Cr	Ni	Mo	Al	Ti	3 B расч.	S/P	
9-11481	0,05	0,14	0,05	14,80	35,60	—	0,98	2,98	0,015	0,006/0,007	Хорошая 5
9-11485	0,05	0,14	0,14	15,15	35,35	1,35	1,25	2,98	0,015	0,005/0,005	Удовлетворительная 6
9-11484	0,05	0,09	0,19	15,35	35,10	3,25	1,25	3,05	0,015	0,005/0,008	То же 7
9-11483	0,06	0,16	0,15	15,20	35,50	5,35	1,30	3,00	0,015	0,005/0,005	С трещинами 8
9-11482	0,03	0,12	0,15	14,95	35,35	7,90	1,30	2,98	0,015	0,008/0,006	С рванинами 9

1) Melt No.; 2) content of elements, %; 3) B, calculated; 4) forgeability; 5) excellent; 6) satisfactory; 7) same; 8) with cracks; 9) with tears.

chemical compositions of some of the alloys studied are listed in Table 7.

Molybdenum raises the hardness and strength of the alloy investigated in the hardened and aged states.

Molybdenum raises the softening temperature of the alloy, shifting it through 50-80° in the zone of higher temperatures. At 5% Mo, rapid softening of the alloy begins above 850°. The adequate hardness of the alloy with 8% Mo is retained up to 900° (280 HB).

All of the alloys investigated with 1-8% Mo harden on aging due to the segregation or decay of the Ni_3 (Ti, Al)-phase solid solution. Like tungsten, molybdenum in the concentrations investigated dissolves completely in the γ-solid solution of the alloy, does not enter the hardening phase, and lowers the solubility of titanium and aluminum. In the alloys investigated, high-temperature strength increases with increasing molybdenum concentration up to 5.0% (Table 8). The heat resistance diminishes with higher molybdenum contents. It is interest-

TABLE 8

1 Номер плавки	Mo, %	2 Длительная прочность	5 Механические свойства при 20°						
		3 Время до разрушения*, часы	σ_b, 4 кг/мм²	σ_s, 4 кг/мм²	δ, %	ψ, %	a_k, 6 кгм/см²	7 твердость после закалки, HB	8 твердость после старения, HB
11485	1,35	168	107,2	77,0	9,3	10,6	4,5	285	331
7-6289	2,78	415	—	—	—	—	—	—	—
11484	3,25	410	129	79	—	16,7	4,6	277	341
7-6991	4,69	395	—	—	—	—	—	—	—
11483	5,35	>167**	113	75	10	9	3	277	341
11482	7,9	>207**	95	86,5	2,6	4	—	321	341

* Tests at 750° and σ = 30 kg/mm².
** Tests continue.

1) Melt No.; 2) long-term strength; 3) time to failure,* hours; 4) kg/mm²; 5) mechanical properties at 20°; 6) kg-m/cm²; 7) hardness after hardening, HB; 8) hardness after aging, HB.

ing to note that in the Fe-Ni-Cr-Ti-Al-base alloys studied, injection of 3-4% W or 3-4% Mo gives the same heat resistance (Fig. 3 and Table 8). After heat treatment (hardening from 1170-1180°, 8 hours, air + 1050°, 4 hours, air + aging at 750°, 16 hours, air), the time to failure at 750° and 30 kg per mm² comes to 400-420 hours for the alloy with 3-4% W and 410 hours for the alloy with 3-4% Mo.

TABLE 9

1 Номер плавки	2 Содержание элементов, %				3 Длительная прочность			5 Механические свойства при 20°C				
	Al	Ti	Mo	W	4 время до разрушения, часы	δ %	ψ %	6 σ_b кг/мм²	6 σ_s кг/мм²	δ, %	ψ, %	7 a_k кгм/см²
6291	0.60	2.70	4.69	—	369	6.2	9.6	125.1	77.8	18.8	24.0	6.2
10261	1.06	2.78	2.16	3.08	355	3.6	3.0	133.6	78.3	22.8	24.9	6.8

Note. 1. Heat-treatment conditions: 1150°, 2.5 hours, air + 1050°, 4 hours, air + aging at 750°, 16 hours, air. 2. Long-term-strength testing at 750° and $\sigma = 30$ kg/mm².

1) Melt No.; 2) content of elements, %; 3) long-term strength; 4) time to failure, hours; 5) mechanical properties at 20°C; 6) kg/mm²; 7) kg-m/cm².

The mechanical properties of these alloys are highly similar. It should be noted that the alloys containing molybdenum are more severely oxidized on heating (in forging and heat treatment) than the alloys with tungsten.

Thus, the alloy on the Fe-Ni-Cr-Ti-Al base with 3-4% Mo has no property advantages over the alloy with 3-4% W.

Simultaneous alloying with tungsten and molybdenum has a favorable influence on the properties of a heat-resistant alloy of the composition studied. The advantage of joint alloying with tungsten (3%) and molybdenum (2-3%) come particularly strongly into evidence at higher test temperatures (+800°), where alloys containing 3% W or 3% Mo alone are less resistant to softening.

It is characteristic that after hardening from 1150°, alloys containing combined additives of 5-6% W and Mo (total) or 5-6% of either of these elements show, in addition to high heat resistance at 750-800°, excellent short-term strength characteristics (σ_b, σ_s), plasticity (δ, ψ) and impact strength at room (Table 9) and elevated temperatures.

Influence of niobium and vanadium

Alloys with the following niobium contents were studied: 0.55, 1.20 and 1.57% (Table 10). In the quantities investigated, niobium hardens the solid solution considerably, raising its hardness and strength. By reducing the solubility of titanium and aluminum in the solid solution, niobium inhibits diffusion processes.

As a result, the heat resistance of the alloy is increased: the time to failure of the alloy without niobium at 750° and $\sigma = 30$ kg/mm^2

TABLE 10

1 Номер плавки	2 Содержание элементов, %					3 Механические свойства при 20°					6
	Al	Ti	W	Nb	B Р/Ф	4 σ_b кг/мм²	4 σ_s кг/мм²	δ, %	ψ, %	5 a_k кгм/см²	твердость $d_{отп}$, мм
8693	0,94	2,90	3,00	—	0,03/0,015	114,4	74,1	20,0	19,0	6—12	—
8695	0,91	2,94	2,40	0,55	0,03/0,017	113,3	85,5	9,15	11,0	3,65	3,4
10259	0,84	2,80	2,67	1,20	0,03/0,025	120,2 118,7	91,8 90,2	9,3 9,3	13,7 13,0	1,7 2,4	3,3 —
10260	0,79	2,83	2,45	1,57	0,03/0,025	116,6 121,2	94,6 90,1	5,7 9,3	7,4 13,0	1,75 1,6	3,2 —

Note. Heat treatment: 1200°, 2.5 hours, air + + 750°, 16 hours, air.

1) Melt No.; 2) content of elements, %; 3) mechanical properties at 20°; 4) kg/mm²; 5) kg-m/cm²; 6) hardness d_{otp}, mm.

is 300-400 hours, while that of the alloy with 0.55% Nb is 450-670 hours.

The strength properties, and the yield point in particular, rise with increasing niobium content (Table 10).

Thus, the alloy without niobium has a yield point at 20° of 74.1 kg/mm^2, while the alloy with 1.6% Nb has 94.6 kg/mm^2. Alloys dosed with niobium in the quantities indicated acquire the highest heat resistance after the three-stage heat-treatment formula.

Also investigated was the influence of vanadium (up to 2%) on the hot-strength and mechanical properties of an alloy based on 15% Cr and 35% Ni with 3% Ti, 3% W and 1% Al.

Addition of 0.5-0.7% V has no influence on long-term strength. Raising the vanadium content to 1.2% increases the heat-resistance properties (Table 11), and simultaneously raises somewhat the long-term plasticity characteristics. The mechanical properties and impact strength show virtually no change (Table 11).

A further increase in vanadium content to 2% results in a drop in long-term strength.

Influence of titanium

We investigated alloys with 15% Cr, 35% Ni, 3% W, 1% Al and variable titanium contents: 1.0, 2, 3 and 4%.

TABLE 11

1 Номер плавки	2 Содержание элементов					3 Длительная прочность			5 Механические свойства при 20°				
	Al	Ti	W	V	B р/ф	4 время до разрушения часы	δ, %	ψ, %	6 σ_b кг/мм²	6 σ_s кг/мм²	δ, %	ψ, %	7 a_k, кгм/см²
4043	0,82	3,07	3,25	0,74	0.03 / 0,021	292 422	3,2 4,4	6.0 8.0	95,1	77,7	4,5	5,4	1,45
4044	0,78	3,3	3,08	1,20	0.03 / 0,016	480 641	8,4 10,8	9.0 9,8	107,1	79,5	6,0	7,9	1,87—3,3
10255	0,41	2,9	3,05	1,90	0.03 / 0,018	136 101 226	5,2 7,2	5.2 15.2	107,0	81,2	7,0	10,0	1,36—1,7

Note. 1. Heat-treatment conditions: 1200°, 2.5 hours, air + aging at 750°, 16 hours, air.
2. Long-term-strength testing at 750° and σ = = 30 kg/mm².

1) Melt No.; 2) content of elements; 3) long-term strength; 4) time to failure, hours; 5) mechanical properties at 20°; 6) kg/mm²; 7) kg-m/cm².

Titanium possesses a relatively low solubility in the Fe-Ni-Cr-W

TABLE 12

1 Номер плавки	2 Содержание элементов, %												
	C	Si	Mn	Cr	Ni	Fe	W	Al	Ti	3 B расч.	Ce расч.	S	P
8157	0.03	0.25	0.25	15.27	35.91	4 Ост.	2.77	0.50	1.15	0.03	0.02	0.007	5 Н. о.
8158	0.03	0.23	0.24	15.55	35.91	»	2.77	0.75	1.89	0.03	0.02	0.005	» »
10256	0.033	0.08	0.09	15.70	35.95	»	2.95	0.70	2.21	0.03	0.02	0.0[illegible]6	» »
8693	0.02	0.10	[illegible]	15.18	35.68	»	3.00	0.94	2.90	0.03	0.02	0.007	0.007
402	0.05	0.56	0.09	15.05	35.82	»	2.80	1.07	3.15	0.03	0.02	0.007	Н. о.
10264	0.07	0.23	0.08	15.70	35.77	»	2.66	0.64	3.97	0.03	0.02	0.006	» »

1) Melt No.; 2) content of elements, %; 3) B, calculated; 4) remainder; 5) not determined; x) traces.

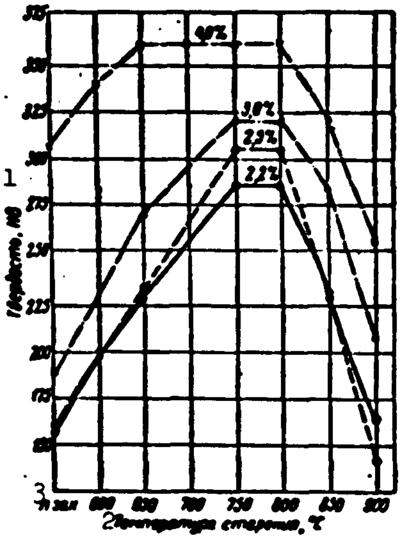

Fig. 4. Hardness of alloys with various titanium contents as a function of aging temperature. Heat treatment: hardening from 1200°, 2.5 hours, air. 1) Hardness HB; 2) aging temperature, °C; 3) after hardening.

solid solution and participates directly in the dispersion-hardening process by formation of intermetallic compounds of the $Ni_3(Ti, Al)$ type with the nickel and aluminum. The hardening $Ni_3(Ti, Al)$ phase has a face-centered cubic lattice similar to that of the γ-solid solution. According to hardness measurements, the solubility of titanium in the alloy base under consideration (with 1% Al) is about 1.5% at 800°. With > 1.5% Ti, the alloys become dispersion-hardening.

An increase in the titanium content results in a considerable increase in the hardness of the alloy (Fig. 4) in the hardened state and after aging.

After aging at 750-800°, the alloy with 2.2% Ti has a hardness of 290 HB; the alloy with 3.0% Ti shows 320 HB, and the alloy with 4% Ti has 360 HB. However, increasing the titanium content does not raise the softening temperature. In all cases, the hardness maximum after aging corresponds to 750-800°; on heating above these temperatures, the hardness begins to drop off as a result of coagulation of the hardening-phase particles.

The long-term strength of the alloys increases with increasing concentration of titanium only up to 3-3.2% Ti (Fig. 5), and declines on further increases in its content.

At high titanium contents (> 3.5%), the plasticity and toughness of the alloys diminish considerably as a result of the appearance of coarse excess-phase segregations in the structure after aging. The strength characteristics of Fe-Ni-Cr-W-Al alloys increase with increasing titanium content in short-term testing (σ_b, σ_s) (Table 13).

The experimental data obtained indicate that in the Fe-Ni-Cr-W-Al-based dispersion-hardening alloys studied, the optimum titanium content, which guarantees the required level of heat-resistance (at 700-750°) and mechanical properties, is 2.7-3.2%.

TABLE 13

1 Номер плавки	Ti, %	Твердость $d_{отп}$, мм 2	3 σ_b, кг/мм²	σ_s 3 кг/мм²	δ, %	ψ, %	4 a_k, кгм/см²
8157	1.15	4.2	81.3	44.1	19.8	24.5	7.5
8158	1.89	3.9	86.1	43.5	34.2	36.0	8.4
10256	2.21	3.6	82.7	64.1	5.5	11.7	2.0
402	3.15	3.4	106.1	79.9	8.5	11.6	2.4

Note. Mechanical properties after heat treatment by the formula: 1200°, 2.5 hours, air + + 750°, 16 hours, air.

1) Melt No.; 2) hardness d_{otp}, mm; 3) kg/mm²; 4) kg-m/cm².

Influence of aluminum

We investigated alloys with 15% Cr, 35% Ni, 3% W, 3% Ti and a variable aluminum content: 0.5, 1.0, 1.5, 2.5, 3.0, 4 and 5.5%. The chemical compositions of the experimental alloys with aluminum are listed

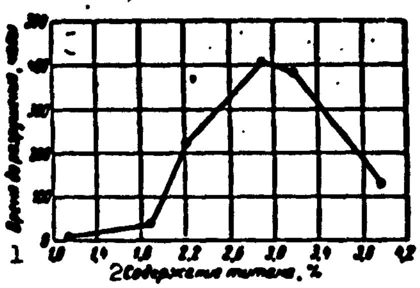

Fig. 5. Time to failure of alloy of EI787 type with various titanium contents. Heat treatment: 1200°, 2.5 hours, air + 750°, 16 hours, air. Testing at 750° and σ = 30 kg/mm². 1) Time to failure, hours; 2) titanium content, %.

in Table 14.

Changing the aluminum content has a considerable influence on the alloy's properties. Increasing the quantity of aluminum results in an increase in the alloy's hardness in the hardened and aged states (Fig. 6). Aluminum raises the softening temperature of the alloy. With 1.6% Al, high hardness is retained after aging at 850 and even 900° (260 HB).

TABLE 14

1 Номер плавки	2 Содержание элементов, %												
	C	Si	Mn	Cr	Ni	Fe	W	Al	Ti	3 B (расч.)	Ce (расч.)	S	P
5-4034	0.025	0.40	0.06	15.70	35.82	4 Ост.	1.82	—	2.03	0.02	0.02	0.005	5 Н. о.
5-7255	0.03	0.22	0.09	15.77	35.15	»	2.02	0.40	2.87	0.02	0.02	0.006	» »
5-1529	0.04	0.10	0.03	14.59	35.93	»	1.93	0.85	3.01	0.02	0.02	0.007	0.004
5-3299	0.04	0.16	0.08	15.63	35.28	»	2.00	1.60	3.00	0.02	0.02	0.010	Н. о.
5-4037	0.032	0.37	0.06	15.70	35.69	»	1.97	2.08	3.05	0.02	0.02	0.006	» »
5-4038	0.035	0.38	0.08	15.72	35.82	»	1.88	2.67	3.03	0.02	0.02	0.007	» »
5-4039	0.03	0.32	0.06	15.90	36.21	»	1.85	3.29	2.55	0.02	0.02	0.016	» »
3300	0.04	0.15	0.03	13.50	35.22	»	3.18	1.70	2.92	0.03	0.02	0.009	» »
4042	0.05	0.35	0.06	13.45	36.21	»	3.0[illegible]	2.00	3.05	0.04	0.02	0.006	» »
1858	0.05	0.16	0.14	12.82	35.84	»	4.26	2.25	3.38	0.03	0.02	0.006	» »
6294	0.03	0.15	0.10	13.10	35.23	»	3.40	2.43	2.67	0.03	0.02	0.005	» »
9278	0.03	0.21	0.18	13.50	35.60	»	3.00	3.27	2.86	0.03	0.02	0.005	» »
9277	0.02	0.27	0.17	13.46	35.45	»	3.24	3.50	2.94	0.03	0.02	0.005	» »
6296	0.02	0.20	0.10	13.25	35.16	»	3.55	3.83	2.73	0.03	0.02	0.005	» »
9276	0.03	0.28	0.19	13.64	35.45	»	3.16	4.60	2.98	0.03	0.02	0.005	» »
7201	0.02	0.25	0.12	13.30	35.59	»	3.31	5.65	2.87	0.03	0.02	0.005	» »

1) Melt No.; 2) content of elements, %; 3) B (calculated); 4) remainder; 5) not determined.

Forming an intermetallic phase with nickel and titanium, aluminum contributes to most rapid and complete unfolding of the aging processes in the alloy.

According to the data of phase chemical analysis,* the quantity of the intermetallic phase $Ni_3(Ti, Al)$ that segregates during aging increases with increasing concentration of aluminum in the alloy. It is characteristic that as the amount of aluminum introduced into the alloy increases, its concentration in the metallic deposits also increases; here, the content of titanium in the deposits declines (Fig. 7). Replacing titanium atoms in the crystal lattice of the intermetallic compound $Ni_3(Ti, Al)$, the aluminum raises its thermal stability, shifting softening of the alloy toward higher temperatures. Herein lies the chief reason for the considerable increase in heat-resistance shown by the alloy as the aluminum content is raised to 2.5-2.8%. On introduction of 3% Al, the heat-resistance properties of the alloy deteriorate sharply due to segregation of a large quantity of excess phase. The microstructure of alloys containing 3.5% Al is clearly two-phased in nature (Fig. 8). The coagulated particles of the excess phase are arranged along the grain boundaries and inside the grains.

There is even more excess phase (Fig. 8) in the structure of the alloy with 5% Al. The highest heat resistance after heat treatment (hardening from 1200°, 2 hours, air + 1050°, 4 hours, air + aging at 800°, 16 hours, air) is shown by the alloy with 2.5-2.8% Al. The time to failure at 800° and σ = 25 kg/mm^2 is 400 hours (Fig. 9). The structure of the alloy with 2.5% Al consists of polyhedra of the γ-solid solution (grain-size rating 1-2), dispersed intermetallic-phase segregations (visible under the electron microscope at 9000 x) and a small quantity of carbides and nitrides of titanium. Alloys containing more than 3% Al have low heat resistance: at 800° and σ = 25 kg/mm^2, the time to failure is 60 hours. In selecting the composition of an alloy for a specific application, it is necessary to take into account the entire ensemble of its properties, including its adaptability to technology. From this standpoint, the technological, heat-resistance and mechanical properties of the alloy with 0.8-1.2% Al satisfy requirements for operation at 700-750° under stress.

In these alloys, the time to failure at 750° and $\sigma = 30\ kg/mm^2$ is over 100 hours.

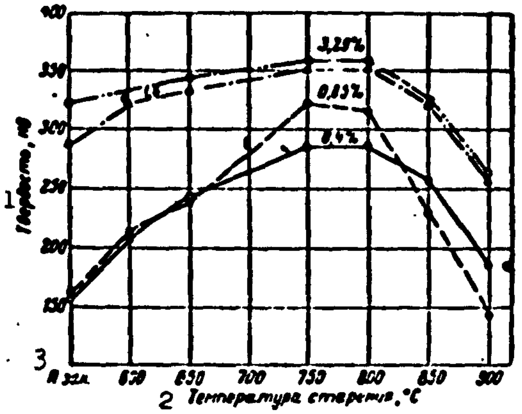

Fig. 6. Hardness of alloys with various aluminum contents as a function of aging temperature. 1) Hardness HB; 2) aging temperature, °C; 3) [after hardening].

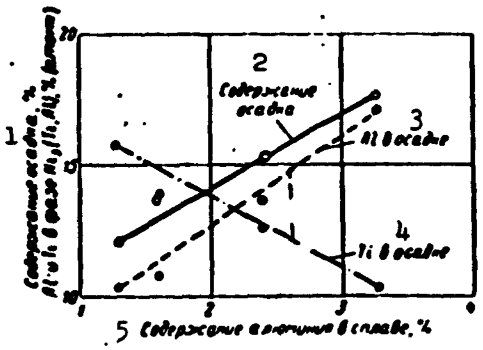

Fig. 7. Amount of deposit and contents of aluminum and titanium in deposit as functions of aluminum content. Heat treatment: hardening from 1200°, 2.5 hours, cooling with furnace at a rate of 180°C/hour to 600°, then cooling in air. 1) Content of deposit, %; Al and Ti in $Ni_3(Ti, Al)$ phase, atom-%; 2) content of deposit; 3) Al in deposit; 4) Ti in deposit; 5) content of aluminum in alloy, %.

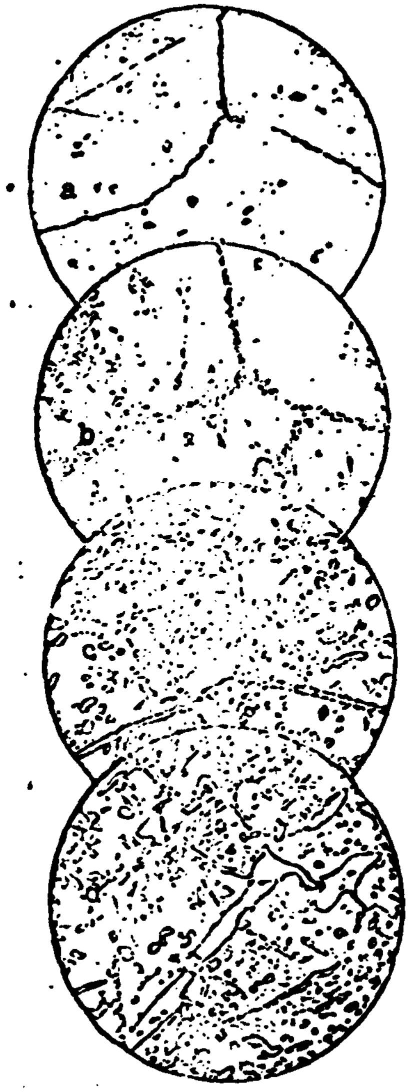

Fig. 8. Microstructure of type EI787 alloys with variable aluminum content. 600 x. Heat treatment: 1200°, 2.5 hours, air + 1050°, 4 hours, air + 300°, 16 hours, air.

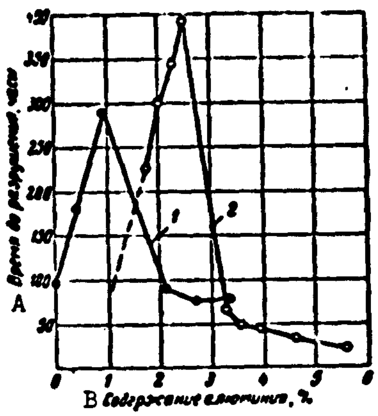

Fig. 9. Time to failure of type EI787 alloy with various aluminum contents: 1) Heat treatment: 1200°, 2.5 hours, air + 750°, 16 hours, air. Testing at 750° and σ = = 30 kg/mm²; 2) heat treatment: 1200°, 2 hours, air + 1050°, 4 hours, air + 800°, 16 hours, air. Testing at 800° and σ = = 25 kg/mm². A) Time to failure, hours; B) aluminum content, %.

Alloys containing 1.7-2.5% Al have higher heat resistance and can be used under stress at 800°. In the alloy with 2.5% Al (hardening from 1200°, 2.5 hours, air + 1050°, 4 hours, air + aging at 750°, 16 hours, air), the time to failure at 750° and σ = 30 kg/mm² is over 1500 hours, while it is 100-200 hours at 800° and 25 kg/mm².

In short-term tests, the strength characteristics (σ_b, σ_s) change little as the content of aluminum in the alloy is increased from 1 to 3%.

The plastic properties (δ, ψ) and impact strength decline with increasing aluminum content in the alloy. With > 3% Al, the alloy becomes brittle (Table 15).

TABLE 15

1 Номер плавки	Al, %	2 Механические свойства при 20°				
		3 σ_b, кг/мм²	3 σ_s, кг/мм²	δ, %	ψ, %	4 a_k, кгм/см²
77204	1,00	118,7	79,6	19,0	18,2	5,7
2308	3,10	111,6	86,2	7,6	8,9	2,0
2309	5,0	123,2	—	5,7	6,8	0,9

Note. Heat treatment: 1180°, 4 hours, air + + 1050°, 4 hours, air + 750°, 16 hours, air.

1) Melt No.; 2) mechanical properties at 20°; 3) kg/mm²; 4) kg-m/cm².

Consequently, alloys with 15% Cr, 35% Ni, 3% W, 3% Ti and ≤ 2.5% Al may find practical application.

Experiments conducted with the object of hardening an alloy on the Fe-Ni-Cr-W base by segregation of a Ni_3Al-type intermetallic phase

TABLE 16

1	2 Содержание элементов, %		3	4	5 Механические свойства при 20°				
	Al	W			6 σ_b	6 σ_s	δ, %	ψ, %	7 a_k
6299	2,95	3,57	5,2	5,2	58,4	23,4	39,3	43,2	18,1
6300	4,80	3,32	4,5	3,5	100,6	64,9	21,2	31,0	5,3
6301	6,50	3,32	3,8	3,5	116,7	78,5	22,0	22,6	1,6
6661	9,15	3,90	3,6	3,4	112,0	75,7	6,2	6,8	0,5
6662	12,3	3,50	3,0	3,0	—	—	—	—	—

Note. Heat treatment: 1200°, 2.5 hours, air (except for melt 662: 1200°, 2.5 hours, air + + 1050°, 4 hours, air). Aging at 800°, 16 hours, air.

1) Melt No.; 2) content of elements, %; 3) hardness after hardening, d_{otp}, mm; 4) hardness after aging, d_{otp}, mm; 5) mechanical properties at 20°; 6) kg/mm²; 7) kg-m/cm².

on decay of the γ-solid solution did not give positive results.

Alloys with 15% Cr, 35% Ni, 3% W and variable (2 to 12%) aluminum were smelted out for the investigation. In this series of titanium-free alloys, aluminum is detrimental to forgeability when its concentration is increased above 9%. Alloys containing less than 9% Al forged quite satisfactorily, while alloys with 12% Al fractured on undergoing deformation.

In Fe-Ni-Cr-W alloys of the composition studied, aluminum increases hardness in the hardened state as its concentration is increased. The alloy with 2.95% Al has a hardness of 131 HB after hardening from 1200° in air; when the Al content was raised to 12%, the hardness rose to 415 HB.

A tendency to dispersion-harden on aging appears in alloys containing more than 4% Al. An alloy with 2.95% Al did not harden on aging (Table 16). The alloy with 4.8% Al (302 HB) underwent considerable hardening during aging (800°, 16 hours, air) after hardening from 1200° (179 HB); this alloy has a two-phased structure. The solubility of aluminum at 800° in an alloy with 15% Cr, 35% Ni, 3% W, remainder Fe is apparently 3.5-4.0%.

Hardening takes place on aging (800°) of an alloy that has been hardened from 1200° with aluminum contents below 9% Al (Table 16). With 12% Al, the solid solution of the alloy is so oversaturated that decay goes to completion (415 HB) on cooling in air from 1200°. Subsequent aging of this alloy at 800° results in no further hardening. The structure of such an alloy consists of the γ-solid solution and a large quantity of second-phase particles. In this state, the alloy is nonmagnetic.

The short-term strength characteristics (σ_b, σ_s) rise with increasing aluminum concentration in the alloy up to 6.5% and show virtually no change thereafter. The plastic properties (δ, ψ) and impact strength drop sharply with increasing aluminum content. After full heat-treatment, the nonhardening single-phase alloy with 2.95% Al has the lowest strength (σ = 50 kg/mm^2, σ_s = 23 kg/mm^2) and the highest plasticity and toughness (δ = 38%, a_k = 18 kg-m/cm^2).

In the dispersion-hardening alloy with 6.5% Al, the strength characteristics are improved by a factor of 2 (σ = 116 kg/mm^2; σ_s = = 78 kg/mm^2), while the plastic properties (δ, ψ) drop by half (δ = = 22%, ψ = 22%). The impact strength drops to 1.6 kg-m/cm^2.

In the alloy with 9% Al, the plastic properties and the impact strength show very low levels (δ = 6%, ψ = 7%, a_k = 0.5 kg-m/cm^2) as a result of the large quantity of excess phase.

Exceedingly low heat resistance is characteristic for this group of alloys.

After hardening from 1200° and aging at 800°, the time to failure at 750° and σ = 30 kg/mm^2 is no longer than 8 hours for all of the alloys containing 3-9% Al.

Here, the residual-plasticity characteristics attain significant magnitudes: δ = 38-43%, ψ = 48-84%. As regards absolute magnitude, δ and ψ increase in dispersion-hardening alloys with aluminum as the aluminum content is raised to 6.5% and thereafter show virtually no change.

Hence alloys of the group studied – on the Fe-Ni-Cr-W base with an aluminum content – are not used in practice.

Influence of boron

We studied the influence of boron on the microstructure and properties of alloys containing 15% Cr, 35% Ni, 3% W, 3% Ti, 1% Al and boron additives as follows: 0.01, 0.02, 0.03, 0.05, 0.07, 0.08, 0.10, 0.15 and 0.20%. The closely similar contents of the basic alloying elements (W, Ti and Al) in the melts studied made possible reliable evaluation of the influence of boron on the properties of heat-resistant alloys based on Fe-Ni-Cr. The resulting alloys with variable boron concentrations are listed in Table 17.

It is known from reports published earlier [7] that boron is a useful alloying component in heat-resistant alloys on the Cr-Ni and Fe-Ni-Cr bases. It is shown in the studies of Pridantsev and Lanskaya [8] that a boron additive to austenitic steel (14% Cr, 18% Ni, 2.5% W, 1% Nb) raises not only grain-boundary strength, but also, to a considerable degree, the strength of the grains themselves as well, i.e., the strength of the solid solution.

According to Nicholson's data, the solubility of boron in iron at 870-1135° is 0.0017-0.0134% [19].

In the Fe-Ni-Cr-W-base alloys studied, a boride eutectic appears at some of the grain joints after heating at 1200° when a 0.03% B (calculated) additive is present.

The quantity of eutectic increases with increasing boron concen-

TABLE 17

1 Номер плавки	2 Содержание элементов, %										
	C	Si	Mn	Cr	Ni	Fe	W	Al	Ti	4 B (расч.)	S
3809	0,03	0,22	0,15	15,26	35,53	Ост.[3]	2,57	0,84	3,05	0,010 0,020 0,030	0,006
3810	0,03	0,20	0,12	15,36	35,53	»	2,63	0,93	3,11	0,050 0,060 0,070	0,009
3811	0,03	0,16	0,11	15,50	35,27	»	2,94	0,99	3,16	0,080 0,10 0,15 0,20	0,006

1) Melt No.; 2) content of elements, %; 3) remainder; 4) B (calculated).

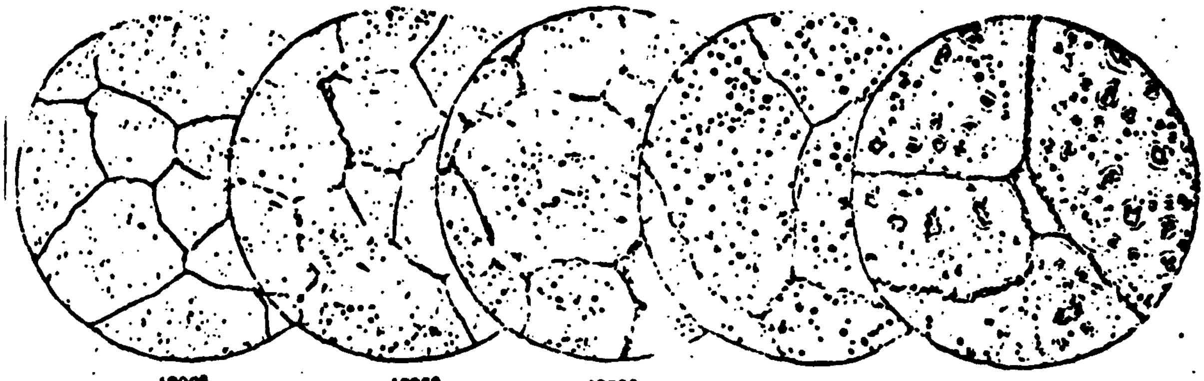

Fig. 10. Microstructure of type EI787 alloys with 0.03% B after heating for 2.5 hours at various temperatures and cooling in air. 100 x.

tration in the alloy and as the hardening temperature is raised when the B content is constant at 0.03% (Fig. 10). After heating to 1250°, the boride-eutectic segregations are found not only at the boundaries and faces between the grains, but also inside them. According to data of spectral and microstructural analyses, we may assume that the limiting solubility of boron in an Fe-Ni-Cr-W-Ti-Al alloy of the composition studied is ~ 0.005-0.008% at 1150°. At higher boron contents, borides and the boride eutectic form.

Forming a low-melting eutectic in the alloy composition studied, boron in higher concentrations (above 0.03% theoretical) increases the

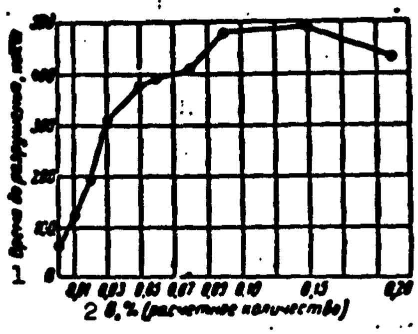

Fig. 11. Time to failure of alloys with various boron contents: heat treatment: 1200°, 2.5 hours, air + 800°, 16 hours, air. Testing at 750° and $\sigma = 30$ kg/mm². 1) Time to failure, hours; 2) B, % (calculated quantity).

tendency of the alloy to overheat and is detrimental to deformability in the hot state.

In the concentration range studied, boron raises heat resistance, and more effectively if it is introduced into the alloy in quantities less than 0.1% (calculated). Alloys with 0.1-0.15% B (calculated) have the longest times to failure (~ 500 hours) in tests at 750° and $\sigma = 30$ kg/mm². Small boron additives have a strong influence on the heat resistance of the Fe-Ni-Cr alloy. On injection of 0.015% of B (calculated), the time to failure at 750° and $\sigma = 30$ kg/mm² is 200 hours, while it is only 50-60 hours in the alloy without boron (Fig. 11).

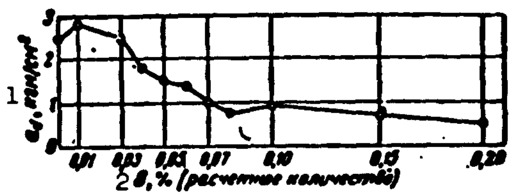

Fig. 12. Impact strength of alloys as a function of boron content. Heat treatment: 1200°, 2.5 hours, air + 800°, 16 hours, air. 1) a_k, kg-m/cm²; 2) B, % (calculated quantity).

It has been established by investigation of the microstructure of the alloys and impact-strength tests (Fig. 12) that on introduction of boron into the alloy in quantities that exceed its solubility, the impact strength drops sharply as a result of the formation of borides and the boride eutectic, which settle along the grain boundaries.

Excessive quantities of boride have a particularly unfavorable influence on the impact strength of the alloy when it is hardened from high temperatures (1200° and higher).

Figures 13 and 14 show the changes in the impact strength and microstructure of alloys with 0.03% B and without it after hardening from temperatures ranging from 1100 to 1250° (Fig. 13) and subsequent aging (Fig. 14).

In alloys that do not contain boron, the grain enlargement with increasing hardening temperature is more intensive than in alloys with 0.03% B. The boride eutectic that forms in an alloy with 0.03% B at temperatures of 1200° and higher inhibits grain growth in the γ-solid solution (Fig. 13). The quantity of the eutectic component in alloys with boron increases with increasing hardening temperature. As a result of the increased grain size with increasing hardening temperature, impact strength falls off in alloys with and without boron. However, despite the coarse grain and the presence of the boride eutectic in the structure, alloys containing 0.03% B (calculated) have high impact-strength values after hardening (to 1225°). The impact strength of an alloy with 0.03% B (calculated) after hardening from 1200 and 1250° is 16-18 and 5-8 kg-m/cm², respectively.

A further increase in impact strength takes place in hardened alloys (with and without boron) on aging, as a result of decay of the solid solution and segregation of a hardening phase. Alloys with 0.03% B (calculated) show satisfactory (Fig. 14) impact-strength levels (above 3 kg-m/cm²) after hardening from 1180° and subsequent aging (800°, 16 hours, air). Hardening from 1250° results in a considerable drop in impact strength (below 1 kg-m/cm²). The data obtained for the heat-resistance and mechanical properties and the microstructure indicate that boron is most effective on injection into the alloy in calculated quantities of 0.01-0.015%. Here, 0.005-0.008% of the B is assimilated into the metal. With such boron contents, the dispersion-hardening Fe-Ni-Cr-W-Ti-Al alloy deforms satisfactorily hot, has high heat resistance at 550-750°, and excellent levels of strength, plas-

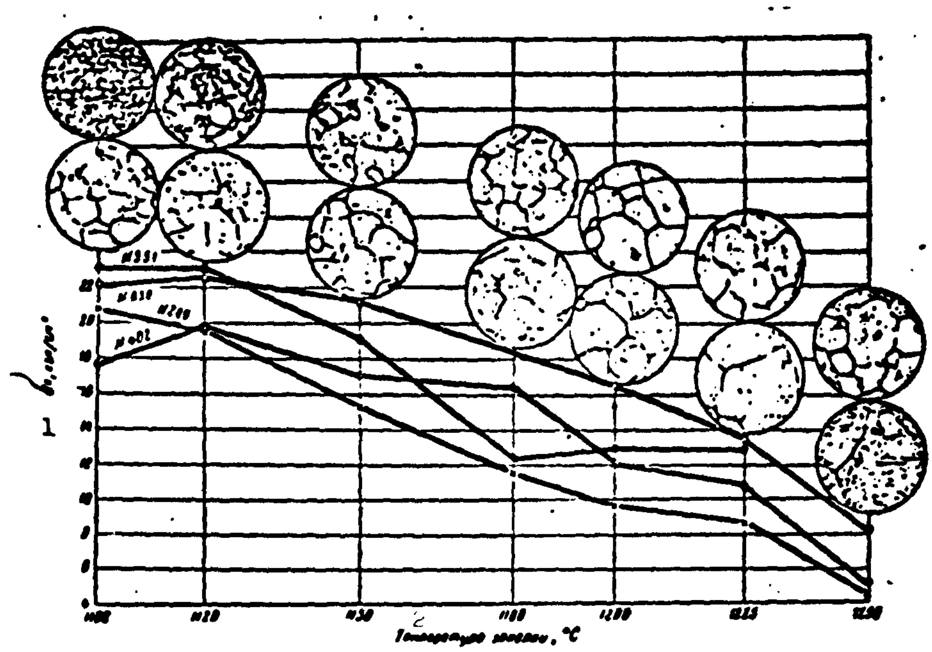

Fig. 13. Impact strengths of alloys with and without boron as a function of hardening temperature (holding at hardening temperature for 2.5 hours, air cooling). Melts 289 and 351 without boron; 830 and 402 with theoretical content of 0.03% B. Upper row of structures, melt 402; lower row, 351. 1) a_k, kg-m/cm^2; 2) hardening temperature, $^\circ$C.

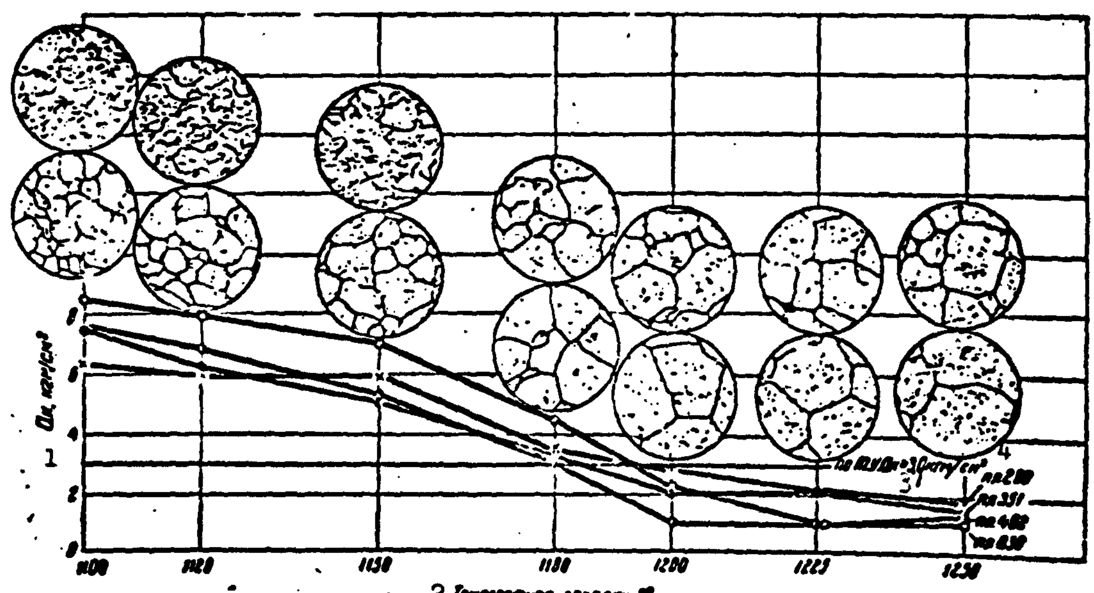

Fig. 14. Impact strengths of aged alloys with and without boron as functions of hardening temperature. Heat treatment: hardening from indicated temperatures, holding at hardening temperature 2.5 hours, air cooling + aging at 800°, 16 hours, air. Melts 289 and 351 without boron; 830 and 402 with theoretical 0.03% B. Upper row of structures, melt 402; lower row, melt 351. 1) a_k, kg-m/cm^2; 2) hardening temperature, $^\circ$C; 3) per technical specifications $a_k \geq 3.0$ kg-m/cm^2; 4) melt 289.

ticity and toughness at room and elevated temperatures.

4. Influence of Other Elements

We investigated laboratory melts with 15% Cr, 35% Ni, 3% W, 3% Ti, 1% Al and variable contents of manganese, silicon and carbon.

Manganese

The influence of manganese in quantities up to 5% on the properties of an alloy containing 15% Cr, 35% Ni, 3% W, 3% Ti and 1% Al was investigated.

TABLE 18

1 Номер плавки	2 Содержание элементов, %												
	C	Si	Mn	Cr	Ni	Fe	W	Al	Ti	3 B (расч.)	Ce (расч.)	S	P
1908	0.05	0.18	0.63	15.26	36.03	4 Ост.	3.08	0.91	2.86	0.015	0.02	0.009	5 Н. о.
1909	0.04	0.10	0.93	15.21	36.10	Ост	3.00	0.89	2.80	0.015	0.02	0.010	» »
1910	0.04	0.11	1.92	15.30	36.03	Ост	3.00	1.08	2.70	0.015	0.02	0.010	» »
1911	0.04	0.15	5.24	15.26	35.89	Ост.	3.00	0.88	2.60	0.015	0.02	0.009	» »

1) Melt No.; 2) content of elements, %; 3) B (calculated); 4) remainder; 5) not determined.

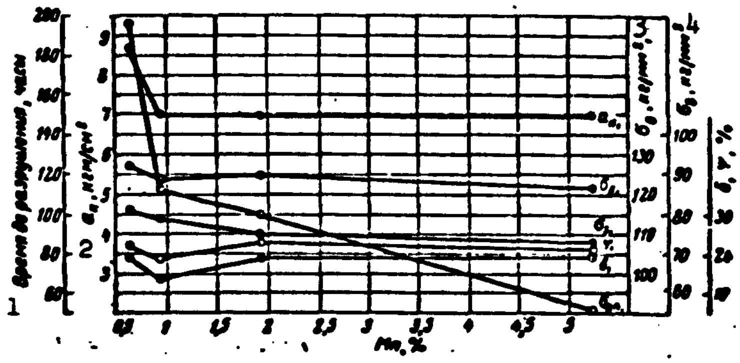

Fig. 15. Properties of type EI787 alloy as functions of manganese content. Heat treatment: 1180°, 4 hours, air + 1050°, 4 hours, air + 750°, 16 hours, air. Long-term-strength testing at 750° and $\sigma = 30$ kg/mm^2. All other properties at 20°C. 1) Time to failure, hours; 2) a_k, kg-m/cm^2; 3) σ_b, kg/mm^2; 4) σ_s, kg/mm^2.

The chemical compositions of the melt metals with various manganese contents are listed in Table 18.

Below 5%, manganese exerts no influence on resistance to deformation: ingots of all melts deformed satisfactorily after heating to 1120-1140°.

The influence of manganese on the properties of the alloys was studied after heat treatment by the following formula: 1180°, 4 hours, air + 1050°, 4 hours, air + 750°, 16 hours, air.

In the concentration range investigated, manganese exerts no influence on the hardness of the alloys after heat treatment. All alloys with less than 5% of manganese have the same tendency to dispersion hardening. After hardening, d_{otp} is 3.6-3.9 mm, and after aging it is 3.3-3.4 mm.

In the range studied, manganese has virtually no influence on the room-temperature mechanical properties: ultimate strength and yield point drop insignificantly as the manganese content is raised to 5%, and the plastic (δ, ψ) and toughness (a_k) property characteristics undergo no changes as the manganese content is increased from 1 to 5%. The long-term strength declines as the manganese content in the alloy is increased (Fig. 15).

The time to failure of an alloy with 5% Mn at 750° and $\sigma =$ $= 30$ kg/mm^2 is 50 hours.

A similar influence of manganese on the heat resistance of alloys on the nickel-chromium base was established [10]. The reasons for the detrimental influence of manganese on heat resistance in the alloys studied are not adequately clear.

In the concentration range studied, the manganese is completely in solid solution in alloys of the type studied.

The solubility of manganese in the quaternary Fe-Cr-Ni-Mn system is 40-45% at 800° [12].

Larger alloying-element contents (Ti, Al, W, Mo) are necessary to prevent loss of heat resistance in alloys containing manganese (5-8%) [12].

This is also confirmed by our data from a study of alloys containing manganese as a substitute for part of the nickel. Manganese has an atomic radius close to those of Fe_{γ} and nickel, but its crystal lattice is not isomorphic to those of Fe_{γ} and nickel; it is this circumstance that A.M.Borzdyka uses to account for the high thermal stability of Cr-Mn austenite as compared with Cr-Ni austenite [11].

Silicon

We studied the properties of alloys with 0.1, 0.2, 0.5, 0.7, 1.0, 1.5 and 1.9 [%] Si (Table 19).

TABLE 19

1 Номер плавки	2 Содержание элементов, %									
	C	Si	Mn	Cr	Ni	Fe	W	Al	Ti	3 B (расч.)
8693	0,02	0.10	4 Сл	15.18	35.68	5 Ост.	3,00	1,03	2,90	0,03
890	0,08	0.17	0.10	15.85	35.26	»	3.61	0,94	3,09	0,03
3812—I	0,03	0.23	0.13	15.53	35,27	»	2,94	0,97	3,02	0,03
3812—II	0,03	0.51	0.13	15.53	35,27	»	2,94	0,97	3,02	0,03
3812—III	0,03	0.73	0.13	15.53	35,27	»	2,94	0,97	3,02	0,03
3813—I	0,03	1.01	0.11	15,3[illegible]	35.40	»	2,83	0,93	3,04	0,03
3813—II	0,03	1.44	0.11	15,3[illegible]	35,4[illegible]	»	2,83	0,93	3,04	0,03
3813—III	0,03	1,87	0,11	15,3[illegible]	35,4[illegible]	»	2,83	0,93	3,04	0,03

1) Melt No.; 2) content of elements, %; 3) B (calculated); 4) traces; 5) remainder.

With silicon contents above 1%, deformation of the alloys is rendered more difficult (10-18-kg ingots). The alloy with 1.8% Si could not be forged. As the silicon content was raised, the heat resistance of the alloy declined (Fig. 16). The time to failure of an alloy with 0.1% Si at 750° and $\sigma = 30$ kg/mm² is 400 hours, while with 1.0% Si it is only 80 hours. The deterioration of forgeability and the drop in heat resistance observed in alloys based on Fe-Ni-Cr is apparently due to the formation of brittle silicides as a result of the

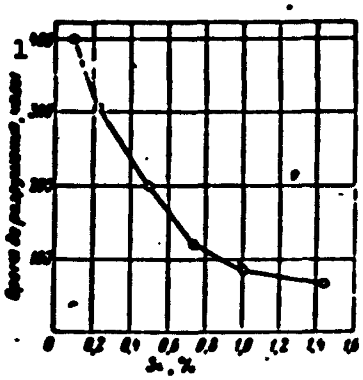

Fig. 16. Time to failure of EI787-type alloys with variable silicon contents. Heat treatment: 1200°, 2.5 hours, air + 800°, 16 hours, air. Testing at 750° and σ = = 30 kg/mm^2. 1) Time to failure, hours.

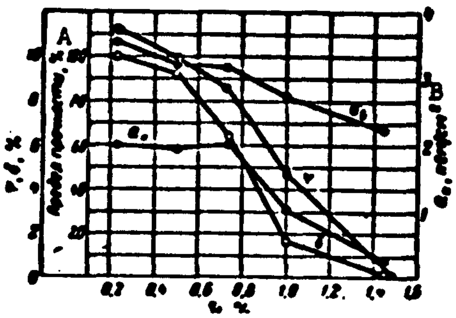

Fig. 17. Mechanical properties of EI787-type alloys with silicon additives. A) Ultimate strength, %; B) a_k, kg-m/cm^2

low solubility of silicon in such a solid solution, just as in alloys based on Ni-Cr [10]. The short-term strength characteristics (σ_b) decline significantly when the silicon content in the alloy is > 0.5-0.7% (Fig. 17).

The plasticity and toughness properties of the alloy drop off much more sharply as the silicon content is raised to 1% (Fig. 17). At 1% Si, these characteristics are at a very low level (δ = 1.7%; ψ = = 4.5%; a_k = 1.0 kg-m/cm^2).

TABLE 20

1 Номер плавки	2 Содержание элементов, %												
	C	Si	Mn	Cr	Ni	Fe	W	Al	Ti	3 B (расч.)	Ce (расч.)	S	P
11697	0.03	0.15	0.19	15.64	34.90	4 Ост.	3.53	1.16	3.07	0.015	0.02	0.003	0.004—0.010
11698	0.13	0.18	0.17	15.69	34.97	»	3.6	1.10	3.0[illegible]	0.015	0.02	0.004	
11699	0.25	0.16	0.23	15.63	35.35	»	3.56	1.24	3.0[illegible]	0.015	0.02	0.004	
11700	0.46	0.14	0.22	15.63	35.28	»	3.54	1.17	3.07	0.015	0.02	0.004	

1) Melt No.; 2) content of elements, %; 3) B (calculated); 4) remainder.

In heat-resistant alloys based on Fe-Ni-Cr, as in alloys based on Ni-Cr, silicon is a detrimental impurity, and its content in the metal should be held to a minimum.

Carbon

We studied the properties of laboratory melts with 15% Cr, 35% Ni, 3% W, 3% Ti, 1% Al and carbon additives (Table 20).

In the concentration range studied (below 0.45%), carbon has practically no influence on the forgeability of the laboratory melts.

In Fe-Ni-Cr alloys with intermetallide hardening [$Ni_3(Ti, Al)$], carbon is detrimental to heat resistance. It is known that titanium forms a stable carbide TiC with carbon and that this carbide does not influence hardening of the alloy. By combining the titanium into the carbides, carbon reduces its content in the solid solution and, consequently, in the hardening intermetallide phase $Ni_3(Ti, Al)$ as well. The drop in the useful titanium content in the alloy as the carbon content rises (above 0.05%) results in a drop in the softening temper-

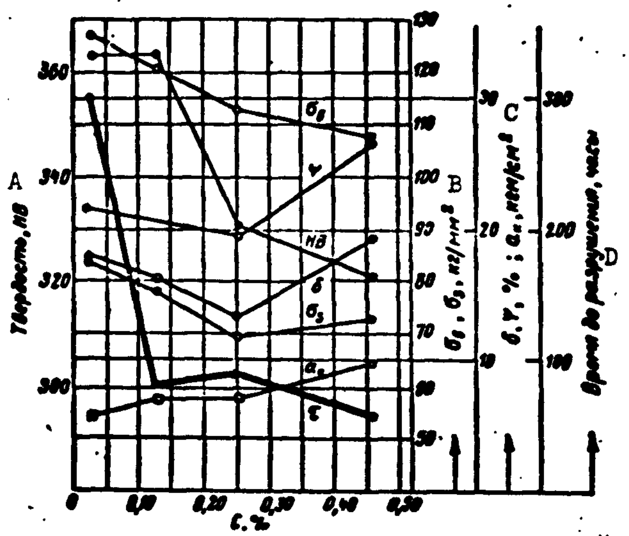

Fig. 18. Properties of EI787 alloy as functions of carbon content: heat treatment: 1180°, 4 hours, air + 1050°, 4 hours, air + 750°, 16 hours, air. Long-term-strength testing at [Key continued on next page]

[Key to Fig. 18 continued]: 750° and $\sigma = 30$ kg/mm^2. A) Hardness HB; B) σ_b, σ_s, kg/mm^2; C) a_k, kg-m/cm^2; D) time to failure, hours.

ature and the heat resistance (Fig. 18).

The times to failure at 750° and $\sigma = 30$ kg/mm^2 are as follows: 300 hours for the alloy with 0.04% C, 85 hours with 0.25% C and 40 hours with 0.45% C.

The changes in hardness, short-term strength and plasticity also characterize (although to a lesser degree) the softening of the alloy with increasing carbon content.

5. Heat Treatment

Iron-chromium-nickel alloys that contain titanium and aluminum are subjected to heat treatment consisting of hardening and aging in view of the changes in the solubility of these elements with temperature.

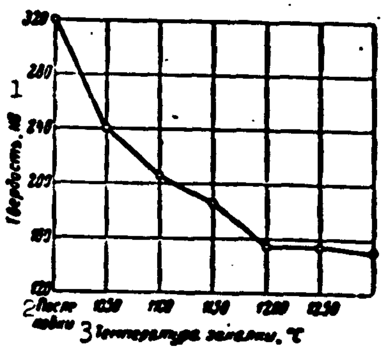

Fig. 19. Hardness of EI787 alloy as a function of hardening temperature (holding time at hardening temperature 2.5 hours). 1) Hardness HB; 2) after forging; 3) hardening temperature, °C.

The basic purpose of hardening is to produce a grain of the required size, ensure sufficiently complete solution of the hardening phase in the γ-solid solution, and to homogenize the solid solution. On cooling in air from the single-phase region, a small quantity of the intermetallide phase $Ni_3(Ti, Al)$ is precipitated from the γ-solid solution. Further decay of the γ-solid solution takes place during aging; as a result, the alloy is subject to maximum hardening.

The hardness and grain growth of the alloy (15-35 base with 3% W, 3% Ti, 1% Al and 0.03% B) are indicated in Figs. 19 and 20 as functions of hardening temperature. When the alloy is hardened from 1050 to 1200°, a drop in hardness occurs due to solution of the excess phases in the solid solution and due to grain growth. Raising the hardening temperature above 1200° has no influence on hardness (Fig. 19). Sufficiently complete solution of the alloying elements and homogenization of the γ-solid solution are achieved with a holding time of 2-2.5 hours at 1200° or 8-10 hours at 1050°.

Cooling in air after high-temperature heating contributes to the formation of a fine-dispersed two-phase structure in the alloy. The alloy acquires rather high hardness in this process (250-280 HB). The lattice constant of the alloy is 3.5886 kX after hardening in air. On rapid cooling in air (20°) after high-temperature heating, the alloy has a low hardness (140-160 HB) corresponding to the undecayed supersaturated γ-solid solution. The largest lattice parameter of the γ-solid solution – 3.5951 kX – corresponds to this state. Rapid cooling sets up severe stresses in the alloy, with the result that cracks form. The brittleness of such an alloy is not eliminated by subsequent tempering.

Given very slow cooling from high temperatures at a rate of 100-180°C/hour, the alloy acquires high hardness (302-321 HB). In this state, the alloy has the structure of the γ-solid solution with the smallest lattice constant – 3.5881 kX – and a large quantity (12.2%) of the intermetallide phase, which has segregated in large particles (Fig. 21). The optimum combination of high hot strength and good plastic properties in the alloy can be obtained after hardening from 1150-1170° in air with subsequent aging.

In the hardened state (cooling in air), these alloys have the polyhedral structure of γ-solid solutions (grain-size rating 2-3) and small segregations of disperse intermetallic-phase particles (Fig. 21); they possess minimum hardness and strength and maximum plastic-

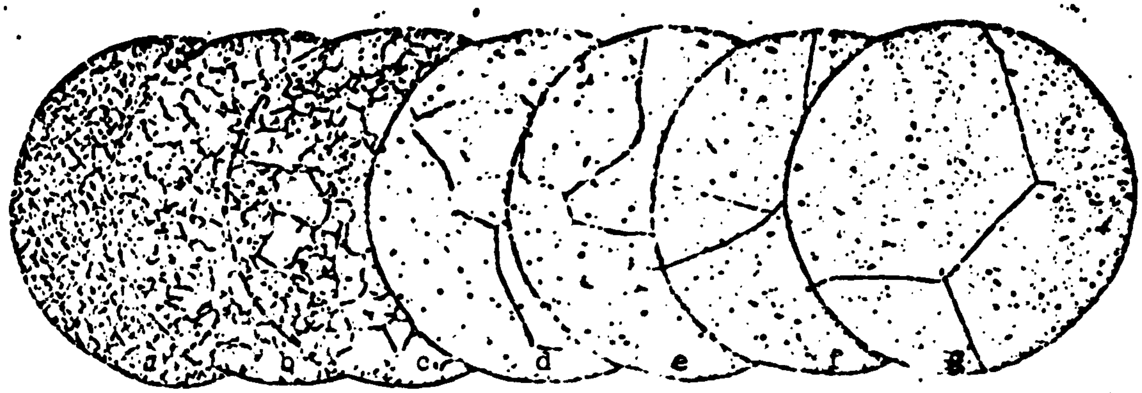

Fig. 20. Grain size in EI787 alloy as a function of hardening temperature.

1 Обозначение	2 Температура закалки, °C	3 Величина зерна, баллы	1 Обозначение	2 Температура закалки, °C	3 Величина зерна, баллы
a а	4 После ковки	6—7	e д	1200	2—3
b б	1050	5	f е	1250	1—2
c в	1100	3—4	g ж	1275	>1
d г	1150	3—2			

1) Key; 2) hardening temperature, °C; 3) grain size, points; 4) after forging.

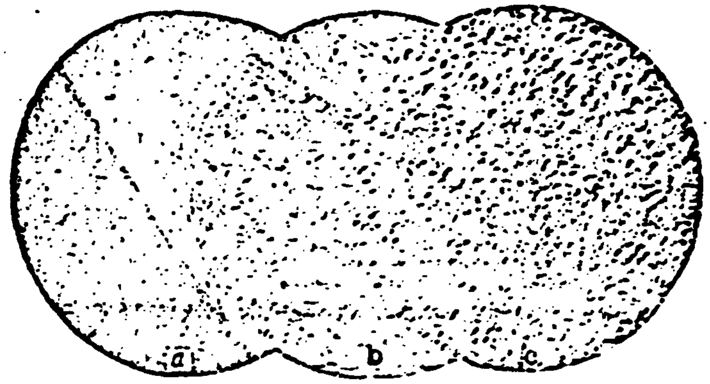

Fig. 21. Microstructure of EI787 alloy. 24,000 x. Heating at 1200°, 2.5 hours and cooling at various rates: a) in water; b) in air; c) with furnace.

ity.

The greatest change in properties of the air-hardened alloys takes place during aging in the range from 600-900° (Fig. 22). Relatively complete segregation of the intermetallic phase requires holding at the aging temperature for 10-12 hours.

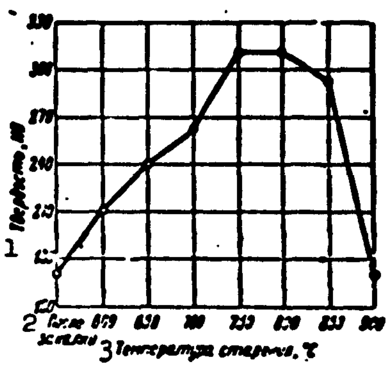

Fig. 22. Hardness of EI787 alloy as a function of aging temperature (16 hours at temperature indicated). 1) Hardness HB; 2) after hardening; 3) aging temperature, °C.

The maximum hardening of the alloys is noted at aging temperatures between 750 and 800°. A rise in the aging temperature to 830° results in a loss of hardness and some softening of the alloy as a result of coagulation of the hardening-phase particles.

Here the characteristics of long-term and short-term strength remain satisfactory, and the plastic properties rise. Aging above 850-900° results in abrupt softening of the alloy as a result of coagulation of the hardening-phase particles and their solution in the γ-solid solution. At aging temperatures above 900°, the process of particle solution in the γ-solid solution predominates.

TABLE 21

1 Содержание элементов (вес.), %					2 Термическая обработка	3 Выход осадка, %	4 Содержание элементов в осадке % (атомн.)						5 Отношение Ni/Ti + Al	6 Карбидная фаза*, %
Cr	Ni	W	Ti	Al			Ni	Ti	Al	Cr	W	Fe		
15	26	3	3,0	0,6	7 1200°, 2,5 часа, воздух + + 750°, 16 час., воздух . . .	4,25	65,53	19,30	5,79	2,75	0,77	5,83	2,61	0,2
15	35	3	3,0	0,19	8 1200°, 2,5 часа, воздух + + 750°, 16 час., воздух . . .	5,08	69,28	17,31	8,66	9 Сл.	0,585	4,525	2,66	0,16
15	35	3	3,0	2,0	10 1200°, 2,5 часа, воздух + + 800°, 16 час., воздух . . .	11,92	68,67	15,892	10,945	»	9 Сл.	4,492	2,6	0,2

*Type of phase $Ni_3(Ti, Al)$.
1) Content of elements, % by weight; 2) heat treatment; 3) yield of deposit, %; 4) content of elements in deposit, atom-%; 5) Ni/Ti + Al ratio; 6) carbide phase*,%; 7) 1200°, 2.5 hours, air + 750°, 16 hours, air; 8) 1200°, 2.5 hours, air + 750°, 16 hours, air; 9) traces; 10) 1200°, 215 hours, air + 800°, 16 hours, air.

According to the data of phase chemical* and x-ray structural** analyses of electrolytically precipitated deposits in the alloys in-

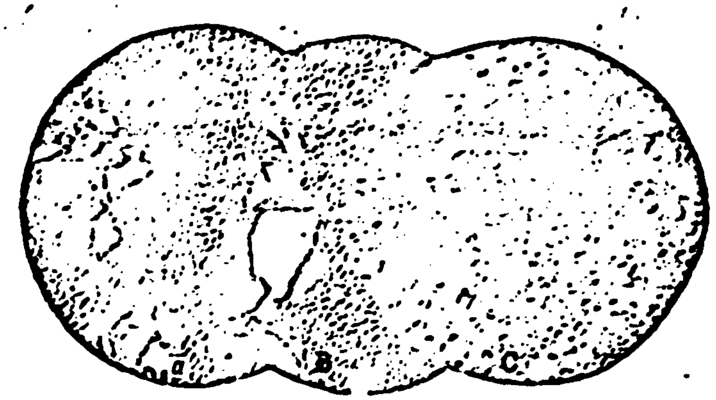

Fig. 23. Microstructure of EI787 alloy. 24,000 x. Heating at 1200°, 2.5 hours, cooling at different rates (a – in water; b – in air; c – with furnace) + aging at 800°, 16 hours, air.

vestigated, hardening with air cooling and aging are attended by segregation of a hardening phase that has a face-centered cubic lattice and corresponds to the intermetallic compound $Ni_3(Ti, Al)$. The basic γ-solid solution has a similar lattice.

The metallic deposits precipitated from the hardened and aged alloy (Table 21) are heavily enriched with nickel, titanium, and aluminum and impoverished in chromium, tungsten and iron. A characteristic observation is that with increasing aluminum concentration in the alloy, the quantity of intermetallic phase that separates on aging increases; here, the content of aluminum in the deposit rises, while that of titanium diminishes (Table 21). Replacing titanium atoms in the crystal lattice of the intermetallic phase, the aluminum assists in raising its thermal stability. For this reason, alloys containing increased quantities of aluminum (1.7-2.5%) soften at higher temperatures. The deposits separated contain 0.2% of TiC.

The ratio of nickel to the sum of the titanium and aluminum in the metallic deposits is 2.6-2.7. If we take into account the contents of chromium and iron in the deposits, this ratio approaches 3. Thus, the chemical composition of the hardening phase corresponds to the formula of the intermetallic compound $Ni_3(Ti, Al)$.

Aging (at 750-830°) of alloys that have been cooled in air and water in hardening results in intensive decay of the γ-solid solution. The intermetallic-phase particles separated here are so dispersed that they become visible only with high magnifications (9000 x) under the electron microscope (Fig. 23). In the aged (750-800°) state, an alloy that has been cooled in air from 1180° during hardening has its greatest heat resistance at 700-750° (time to failure at 750° and σ = 30 kg/mm^2 longer than 100 hours) and high properties in short-term testing (at 20°C: $\sigma_b \geq 115$ kg/mm^2; $\sigma_s \geq 70$ kg/mm^2; $\delta \geq 10\%$; $\psi \geq 15\%$; $a_k \geq 3$ kg-m/cm^2). On slow cooling at a rate of 100-180°C/hour after high-temperature heating, the decay of the γ-solid solution goes almost to completion. For this reason, aging at 750-800° does not result in any significant separation of the hardening phase. The yield of deposit after heating at 1200° and furnace cooling comes to 12.2% and shows virtually no change after additional aging at 800° (12.27%). Nor does the lattice constant of the γ-solid solution show any change (3.5881 kX). Without having any practical effect on the quantity of phase segregated, aging results in coarsening of its particles and modifies somewhat the manner in which they are distributed in the structure (Fig. 23). In the presence of such a structure, the alloy has low long-term (10-20 hours at 750° and 30 kg/mm^2) and short-term strength and high plastic properties. Comparison of the results of long-term and short-term strength testing with the data of phase chemical, x-ray, and microstructural analyses indicates that the properties of the dispersion-hardening alloys based on Fe-Ni-Cr (like the alloys based on Ni-Cr) depend on grain size and the degree to which the γ-solid solution is alloyed, the quantity of hardening phase segregated (during heat treatment), its nature (carbide, intermetallide), the dimensions of its particles and the manner in which they are distributed in the structure.

TABLE 22

1 Режим обработки	2 Механические свойства при 20°					Время до разрушения (часы) при 750° и σ = 30 кг/мм² 4
	σ_b, кг/мм² 3	σ_s, кг/мм² 3	δ, %	ψ, %	a_k, кг/мм² 3	
5 1180°, 8 час., воздух + + 1050°, 4 часа, воздух + 750°, 16 час., воздух	119	79	12	14,5	4,2	280*
6 1180°, 8 час., воздух + +750°, 16 час., воздух	107	76	8,8	10,4	3,3	99

*Many of the specimens did not fail.

1) Treatment formula; 2) mechanical properties at 20°; 3) kg/mm²; 4) time to failure (hours) at 750° and σ = 30 kg/mm²; 5) 1180°, 8 hours, air + 1050°, 4 hours, air + 750°, 16 hours, air; 6) 1180°, 8 hours, air + 750°, 16 hours, air.

TABLE 23

1 Марка сплава	2 Содержание элементов, %													
	C	Si	Mn	S	P	Cr	Ni	Fe	W	Al	Ti	B 3 (расч.)	Ce (расч.)	Ba (расч.)
4 ЭИ786	≤0,08	≤0,6	≤0,6	≤0,010	≤0,020	12—16	26—29	Ост.	2—4	0,5—1,2	2,6—3,2	≤0,03	≤0,02	≤0,2
ЭИ787	≤0,08	≤0,6	≤0,6	≤0,010	≤0,020	12—16	33—37	»	2—4	0,7—1,4	2,6—3,2	≤0,03	≤0,02	≤0,2
ЭИ812	≤0,08	≤0,6	≤0,6	≤0,010	≤0,020	12—16	33—36	»	2—4	1,7—2,5	2,6—3,2	≤0,03	≤0,02	≤0,2

1) Alloy type; 2) content of elements, %; 3) B (calculated); 4) EI786.

The properties of alloys based on Fe-Ni-Cr can be varied over a wide range by selecting the appropriate heat-treatment formulas.

According to the test results, the long-term and short-term strengths of the alloys studied increase with increasing quantity of the hardening phase and increasing dispersion of its particles, while the plastic properties drop sharply.

The use of heat treatment that results in coarsening of all particles of the hardening phase segregated (cooling with the furnace) gives a sharp drop in heat resistance and elevated plastic properties.

It was found possible as a result of the tests carried out to obtain a structure with segregations of hardening-phase particles having various dispersions by applying a second hardening treatment from 1050°.

The alloy has such a structure after heat treatment by the formula:

1. Hardening from 1150-1180°, 4 hours, air.
2. A 2nd hardening from 1050°, 4 hours, air.
3. Aging at 750-830°, 16 hours, air.

The presence of coarse coagulated particles of the hardening phase in addition to fine-dispersed particles in the structure of the alloy after the above heat treatment enables us to obtain good hot strength at 550-750° and high plastic and toughness properties (Table 22).

After the heat treatment indicated, the alloy's structure consists of grains of the γ-solid solution, fine and coarse particles of the intermetallic phase $Ni_3(Ti, Al)$, and a small quantity of titanium carbides and nitrides.

The tests resulted in the formulation of 3 new alloys: EI786, EI787 and EI812.*

The chemical compositions of these alloys are listed in Table 23.

The nickel content (26-37%) is selected so as to ensure a stable austenitic structure, taking into account the high contents of ferrite-forming elements (titanium, aluminum, tungsten, chromium) in the alloys.

Establishment of the chromium content (12-16%) is necessary to ensure adequate hot strength and, in particular, adequate high-temperature corrosion resistance in the alloys.

The alloys must contain minimal amounts of carbon, silicon, manganese, sulfur and phosphorus.

The austenite-class heat-resistant dispersion-hardening alloys that were formulated on the iron-nickel-chromium base are recommended for short-term and long-term service at the following temperatures in °C:

1 Сплавы	2 До 100—200 час.	3 До 10000 час.
4 ЭИ786	500—750	500—700
ЭИ787	650—800	650—750
ЭИ812	750—850	750—800

1) Alloy; 2) less than 100-200 hours; 3) less than 10,000 hours; 4) EI786.

The EI786 alloy is cheapest, since it contains the smallest quantity of nickel, but alloys EI787 and EI812 are more heat-resistant. The alloys developed can be used as materials for gas-turbine engine components.

6. Properties of the Alloys Developed

Alloy EI787 (Kh15N35V3T3YuR)

The mechanical properties listed in Table 24 were obtained in testing rolled metal from industrial melts produced by the "Elektro-

TABLE 24

1 Температура испытания, °C	σ_b, 2 кг/мм²	σ_s, 2 кг/мм²	δ, %	ψ, %	3 a_k, кгм/см²	4 Твердость, HB $d_{отп}$, мм
5 После обработки по режиму I						
20	110—122	71—85	8,2—20,2	9,8—22,0	3,3—5,7	3,3—3,6
600	100—110	62—83	—	12—16	—	—
700	92—97	73—83	5,0—7,5	9—11	—	—
750	85—89	70—80	4—5	6—10	3—4	—
6 После обработки по режиму II						
20	106—124	61—80	11,5—22,0	15—29	3,8—7,0	3,35—3,6
600	100—107	69—79	12—16	17—26	5—6	—
700	74—92	71—79	6—15	10—23	5—6	—
750	69—74	66—72	6—10	8—20	5—6	—

I. First hardening from 1170-1180°, 4-8 hours, air. Second hardening from 1050°, 4 hours, air. Aging at 750-800°, 16 hours, air. II. First hardening from 1150-1160°, 10-6 hours, air. Second hardening from 1050°, 4 hours holding, air. Aging at 830°, 16 hours, air. [Key on following page]

[Key to Table 24]: 1) Test temperature, ^{o}C; 2) kg/mm^2; 3) $kg\text{-}m/cm^2$; 4) hardness HB, d_{otp}, mm; 5) after treatment by Formula I; 6) after treatment by Formula II.

TABLE 25

		1 Температура испытания, °С				
		550	600	700	750	800
2 Гладкие образцы	3 Предел длительной прочности, кг/мм², за 100 час.	80—85	65—68	38—40	30—31	21—24
4 Образцы с надрезом r=0,5 мм	5 Напряжение, кг/мм²	80	65	40	30	22—24
	6 Время до разрушения, часы	380 снят 7	>350	186	>240	>320+327

1) Test temperature, ^{o}C; 2) smooth specimens; 3) ultimate long-term strength, kg/mm^2, 100 hours; 4) notched specimens with r = = 0.5 mm; 5) stress, kg/mm^2; 6) time to failure, hours; 7) removed.

TABLE 26

1 Температура испытания, °С	2 Напряжение кг/мм²	3 Время до разрушения, часы; испытания образцов	
		4 гладких	5 с надрезом (r = 0,5 мм)
550	75	100—259 6	260 снят—334 снят
600	60	126—405 снят	186 » —337 »
700	36	129—393 »	167—312 »
700	40	128—280	130—375 »
750	30	117—282 снят	122—309 »

1) Test temperature, ^{o}C; 2) stress, kg/mm^2; 3) time to failure, hours; testing of; 4) smooth specimens; 5) notched specimens (r = 0.5 mm); 6) removed.

stal'" [Electric Steel] Plant after heat treatment by the formulas listed.

The latter formula (II) was developed to improve the plastic and toughness properties of the alloy.

Long-term Strength

Table 25 lists the results of long-term-strength tests on smooth and notched specimens after heat treatment by Formula I.

Table 26 presents the results of long-term-strength tests on smooth and notched specimens, as obtained on forged (diameter 90 mm) metal after heat treatment by Formula II.

These data indicate that the EI787 alloy has high long-term strength and is not sensitive to stress concentrations at test temperatures from 550 to 800°.

TABLE 27

1 Режим термической обработки	2 Температура испытания, °C	3 $\sigma_{0,2/100}$ по общей деформации	4 $\sigma_{0,2/100}$ по остаточной деформации	5 σ_{-1} на базе 10^7 циклов
I	550	—	77—78	30
	600	—	70	30
	650	—	55—56	—
	700	—	40	28—30
	750	25	—	30—31
	800	13—14	—	25—27
II	550	—	65	28
	600	—	60	—
	700	30	—	—

1) Heat-treatment formula; 2) test temperature, °C; 3) $\sigma_{0.2/100}$ with respect to total deformation; 4) $\sigma_{0.2/100}$ with respect to residual deformation; 5) σ_{-1} on 10^7-cycle base.

The creep and fatigue characteristics of EI787 alloy after the heat treatments are listed in Table 27.

The physical properties of this alloy are as follows:

Specific gravity 8.04 g/cm^3.

Modulus of elasticity E, kg/mm^2, at various temperatures:

1 Температура, °C	2 E, кг/мм²	1 Температура, °C	2 E, кг/мм²
20	21850	500	18600
100	21000	600	17300
200	20250	700	16800
300	19900	750	15600
400	19250	800	15150

1) Temperature, °C; 2) E, kg/mm^2.

Coefficient of linear expansion $\alpha \cdot 10^6$ in the temperature ranges, °C:

20—100	10,8	20—600	18,1
20—200	14,85	20—700	18,2
20—300	17,4	20—800	18,7
20—400	17,43	20—900	20,55
20—500	17,8		

Thermal conductivity λ, kal/cm-sec-degree:

1 Температура, °C	λ	1 Температура, °C	λ
20	0,030	500	0,054
100	0,037	600	0,059
200	0,042	700	0,062
300	0,046	800	0,066
400	0,050		

1) temperature, °C.

Alloy EI786 (Kh15N26V3T3YuR)

Table 28 presents properties obtained in tests of specimens taken from forged rods 15-20 mm in diameter after heat treatment by the formula: 1200°, 2.5 hours, air + 750°, 16 hours, air (Table 28).

TABLE 28

1 Температура испытания, °C	2 σ_b, кг/мм²	3 σ_s, кг/мм²	δ, %	ψ, %	4 a_k, кгм/см²
20	100—120	70—80	10—18	10—22	3,0—5,5
700	83—88	70—78	2.5—6	4—7	—
750	70—80	68—73	4—8	6—12	3,3—5,4

1) Test temperature, °C; 2) kg/mm²; 3) kg/mm²;
4) kg-m/cm².

Hardness after heat treatment: d_{otp} = 3.4-3.6 mm; grain-size rating 3-2.

Time to failure at 750° and σ = 30 kg/mm² is 86-320 hours.

Ultimate long-term strengths of alloy at 750° is 28-32 kg/mm² for 100 hours.

Fatigue limit at 750° on 10^7-cycle base is 30-31 kg/mm².

Elastic modulus E, kg/mm², at various temperatures:

1 Температура °C	2 E, кг/мм²	1 Температура °C	2 E, кг/мм²
20	21500	500	17850
100	20350	600	17100
200	20000	700	16300
300	19400	750	16100
400	18600		

1) Temperature, °C; 2) E, kg/mm².

Specific gravity 8.02 g/cm^3.

Coefficient of linear expansion $\alpha \cdot 10^6$

1 Интервал температур, °C	$\alpha \cdot 10^6$	1 Интервал температур	$\alpha \cdot 10^6$
20—100	14,27	20—600	16,27
20—200	14,76	20—700	16,80
20—300	15,24	20—800	17,20
20—400	15,70	20—900	19,20
20—500	16,16		

1) Temperature range, °C.

Alloy EI812 (Kh15N35V3T3Yu2R)

Alloys of this type with high aluminum contents (up to 2.5%) have high long-term-strength values. The properties listed in Table 29 were determined on forged metal 15-20 mm in diameter after heat treatment

TABLE 29

1 Температура испытания, °C	σ_b, 2 кг/мм²	σ_s, 3 кг/мм²	δ, %	ψ, %	4 a_k, кгм/см²
20	103,0	67,2	8,0	9,7	2,0
20	106,8	65,5	8,6	10,0	2,0
20	99,5	63,1	10,0	11,7	2,23
20	98,3	62,6	9,2	11,7	2,13

1) Temperature, °C; 2) kg/mm^2; 3) kg/mm^2; 4) kg-m/cm^2.

by the formula: 1200°, 2 hours, air + 1050°, 4 hours, air + 800°, 16 hours, air.

Coefficient of linear expansion $\alpha \cdot 10^6$ in the temperature ranges:

1 Интервал температур, °C	$\alpha \cdot 10^6$	Интервал температур, °C	$\alpha \cdot 10^6$
20—100	11,78	20—600	15,13
20—200	13,00	20—700	15,60
20—300	14,00	20—800	15,83
20—400	14,49	20—900	17,47
20—500	14,94	20—1000	19,15

1) Temperature range, °C.

Specific gravity, 7.98 g/cm^3.

Ultimate long-term strength, kg/mm^2:

1 При 800°
2 100 час. . . . 28—32
200 час. . . . 24—27
300 час . . . 23—26
При 750°
100 час. . . . 35—38

1) At 800°; 2) 100 hours.

The times to failure of alloy EI812 at 800° are listed in Table 30.

Of the three alloys investigated, EI812 has the highest heat resistance; it is followed by EI787 and EI786.

Alloy EI812 may be used at 800-850°, and alloys EI787 and EI786 at 550-750°.

Alloy EI787 has the highest short-term strength.

The alloys developed are recommended for fabrication of gas-turbine engine components.

Conclusions

1. High heat resistance may be obtained in Fe-Ni-Cr alloys on 15-25 and 15-35 bases by composite alloying:

TABLE 30

1 Термическая обработка	2 Напряжение кг/мм²	3 Время до разрушения час. — мин.	δ, %	ψ, %
1200°, 2,5 часа, воздух 800°, 16 час., воздух 4 5	30	68—10 94—30 88—40 83—05 88—50	1,6 1,6 — 0,8 0,8	1,6 1,6 — 5,6 2,0
1200°, 2 часа, воздух 1050°, 4 часа, воздух 800°, 16 час., воздух	30	120—35 145—45 213—00 167—30	9,6 4,8 4,0 6,0	6,8 5,9 6,4 10,4
1200°, 2,5 часа, воздух 800°, 16 час., воздух	25	158—00	4,0	3,6
1200°, 2 часа, воздух 1050°, 4 часа, воздух 800°, 16 час., воздух	25	226—50 393—15 133—30	2,4 3,6 6,8	2,0 6,4 6,8

1) Heat treatment; 2) stress, kg/mm²; 3) time to failure, hours-minutes; 4) hours; 5) air.

a. elements that dissolve in relatively large quantities (up to 6% W; to 6% Mo; 6-10% Mo + W; to 2.0% Nb), which retards diffusion of titanium and aluminum into the γ-solid solution and thereby inhibits softening of the alloy.

b. elements with limited solubility (2.6-3.2% Ti; 1-2.8% Al), which form a hardening intermetallic phase $Ni_3(Ti, Al)$ with nickel.

c. boron in quantities that do not exceed its solubility in the Fe-Ni-Cr solid solution (0.005-0.007%) and contribute to increased heat-resistance and plastic properties.

2. Heat-resistant alloys were formulated on the 15-25 (EI786) and 15-35 (EI787 and EI812) bases.

The long-term-strength limits in kg/mm^2 of the alloys for 100 hours at 750° are as follows:

[1]ЭИ786 28
ЭИ787 . . . . 30—34
ЭИ812 . . . . 35—38

1) EI786.

3. The dispersion-hardening alloys EI786, EI787 and EI812 harden on heat treatment due to segregation of an intermetallic phase from the γ-solid solution; this phase has a face-centered cubic lattice (similar to that of the γ-solid solution) and corresponds to the chemical composition $Ni_3(Ti, Al)$.

The properties of the above heat-resistant alloys depend on the grain size of the γ-solid solution, the quantity of the $Ni_3(Ti, Al)$ intermetallic phase that segregates on heat treatment, the size of its particles, and the manner in which they are distributed in the structure.

4. The type EI786, EI787 and EI812 alloys have been adapted to metallurgical production, and their combined heat-resistance, mechanical and plastic properties satisfy the specifications set forth for

materials to operate at high temperatures under stress.

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Manuscript Page No.	[Footnotes]
19	Performed by R.Ye. Grabarovskaya.
38	*Performed by R.Ye. Grabarovskaya.

38 **Performed by R.M. Rozenblyum and S.B. Maslenkov.
42 The alloys were developed in collaboration with the "Elektrostal'" plant and the VIAM [All-Union Scientific-Research Institute for Aviation Materials].

Manuscript Page No.	[List of Transliterated Symbols]
15	отп = otp = otpusk = tempering

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